ALLIS-CHALMERS

# Electrical REVIEW

*First Quarter*, 1949

# These FOUR FACTS

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A 2649

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**DFR — station type single phase regulator.*
*AFR — for 3 phase regulation.*

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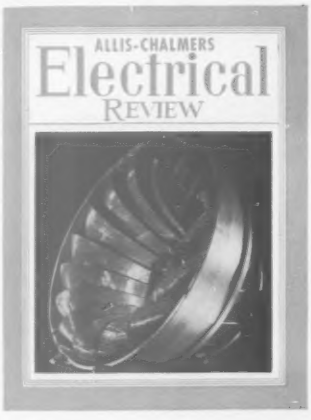
***Originators of 5/8% Step Regulation***




**LARGE CAST STEEL** Francis runner shown having its vanes ground smooth in the erecting shop is the first of four identical units under construction for TVA's Wilson Dam hydro-electric project. Runners will be used in four additional 35,000-hp, 92-ft. head, 100-rpm turbines purchased by the administration to augment six similar units already in use.

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Allis-Chalmers

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# ALLIS-CHALMERS Electrical REVIEW

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# "Coordinated" Insulation–
# NEW TRANSFORMER MILESTONE

**Tailor-made insulation advances realization of quest for smaller, lighter transformers.**

S. L. FOSTER
Transformer Section
Allis-Chalmers Mfg. Co.

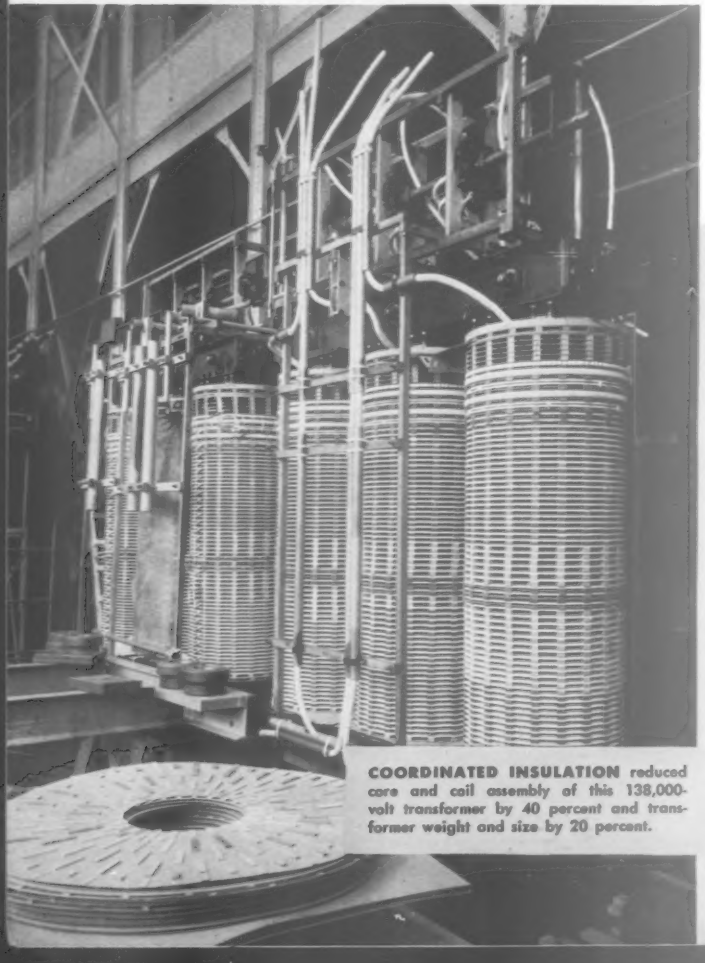
MANY of today's transmission and distribution engineers remember the days when every lightning storm threatened the loss of one or more transformers on a system. Transformer design advances, particularly improvements in transformer insulation, reduce such breakdowns to just a memory today. Further improvements in insulation are continuing in spite of the fact that transformer construction is so reliable today that banks of single phase transformers are usually placed in service without spare units.

Most significant among improvements in insulation has been the development of "coordinated" insulation. Because of its development, transformers of the future will be smaller and lighter, provide higher efficiency and assure even greater insulation against lightning surges. A review of transformer insulating practices of the past reveals the significant contributions of coordinated insulation to the design and construction of modern transformers.

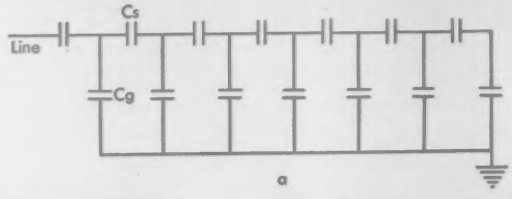
## Stealing thunder from storms

The realization that lightning was the greatest nemesis of transformers started many engineers to study its behaviour characteristics. Several means of limiting voltages on transmission lines resulted from these investigations, with the most elementary of these utilizing proper size insulators for the operating voltages. These insulators have a tendency to arc over when an excessively high voltage is placed on the line, shorting the line to ground and preventing the voltage from becoming too high. However, this often damages the insulators or bushings. Arcing horns placed over insulators or bushings keep the arc away from the insulator and prevent damage to it. Arcing horns provide a fair amount of protection but usually require that the breaker be opened on the line to extinguish the arc, since the normal operating voltage will maintain an arc over the arcing horns which are set to protect the insulators or bushings.

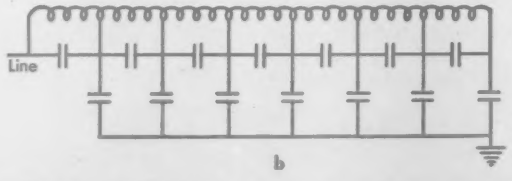
Protector tubes or lightning arresters have proven much better for limiting voltages on transmission lines. After



**COORDINATED INSULATION** reduced core and coil assembly of this 138,000-volt transformer by 40 percent and transformer weight and size by 20 percent.




**EQUIVALENT CIRCUIT** for the capacitance of transformer windings represents a basic principle of design for units using coordinated insulation. Insulation distances affect circuit characteristics. **(FIGURE 1a)**




**COMPLETE EQUIVALENT** circuit of a transformer for use in calculating voltage distribution throughout the winding is another design improvement which permits use of new insulation. **(FIGURE 1b)**

sufficient power has been diverted from the line to drop the voltage to normal, they reseal automatically and prevent further grounding of the line.

## Size of device limits effectiveness

These protective devices restrict surge voltages within certain limits. However, the protective device must be of such size as to prevent arcing over at normal operating voltage. With this size of protective device the lightning surges allowed to pass are several times normal operating voltage. Therefore, transformers must be able to withstand the lightning surges passed by the protective device.

In order to design a transformer which will withstand these surges, it is necessary to know the nature of the surge. Measurements made of actual lightning strokes and surges after they have been modified by protective devices have shown that lightning striking a transmission line is similar to an ocean wave striking a beach. The wave has an exceedingly steep front and the height rises rapidly as the wave approaches but subsides slowly after the crest has passed. When a lightning surge strikes a transmission line and ultimately the transformer, the voltage increases very rapidly at first, then diminishes slowly after the crest or peak of the wave has passed.

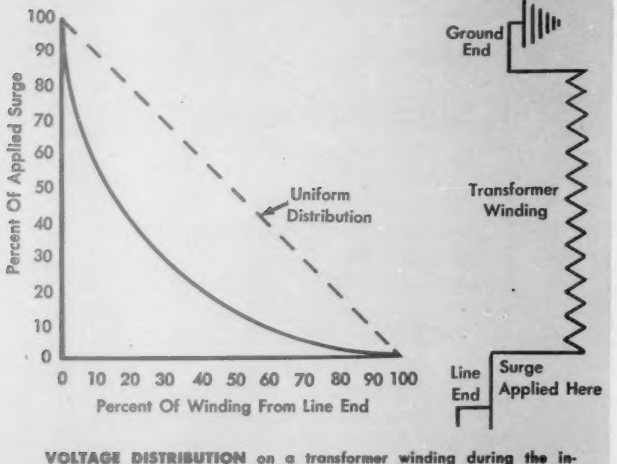
Once lightning behavior was understood, investigations of transformer reaction to lightning surges were made. First, a small, synthetically generated lightning surge was applied to a transformer and the resulting voltage at various parts of the windings was measured. Analysis of voltage measurements revealed that the normal conception of a transformer as an inductive impedance only must be supplemented by the capacitive effect of the windings during surge conditions. To obtain these capacitances, the arrangement of the winding was examined with the various components considered as parts of condensers.

Each turn of a winding can be considered to be a plate of a multiple plate condenser. Also, each turn can be regarded as one plate and the core or supporting framework of the coils another plate of a condenser. When these static condensers are connected in a circuit (Figure 1a), they will simulate the capacitive conditions in the transformer. $C_s$ is the series capacitance between turns and $C_g$ is the shunt capacitance of the turns to ground. A circuit similar to that in Figure 1b results when the inductance of the windings is added to this circuit.

Voltage distribution throughout the winding can be found by mathematically applying the voltages generated in a lightning surge to this circuit. In an average surge, the voltage rises to the maximum in approximately two microseconds. Thus, the front of the wave is equivalent to a voltage with a frequency of more than 100,000 cycles per second. At this frequency, the impedance of the inductive part of the equivalent circuit becomes so high that it can be considered infinite and, therefore, neglected.

At beginning of the surge, the distribution of voltage throughout the winding is determined by the capacitance of the windings only. The voltage to ground of each turn can be calculated by using the capacitance circuit of Figure 1a. If these voltages are plotted, a curve as shown in Figure 2 will result. This shows that for the front or initial part of the surge the voltage between turns is not uniform throughout the winding, the turn-to-turn stress being highest near the line end of the winding.

By changing the values of the capacitances, the voltage distribution during this rising portion of the wave or initial condition can be changed. A large capacitance to ground and small capacitance between turns causes a large voltage stress between turns near the line end of the winding. An example of this condition is a core type transformer with drum winding shown in Figure 3a. A transformer with electrostatic shielding plate (Figure 3b) shell type has the opposite condition of capacitance distribution. Here the capacitance between turns is larger and the capacitance of the turns to ground is smaller. This transformer, with proper arrangement of winding, can be made to have a distribution during the starting or initial part of a surge that is almost uniform throughout the winding. A sectional winding used in a core type transformer, as shown in Figure 3c, has a distribution between these two extremes.

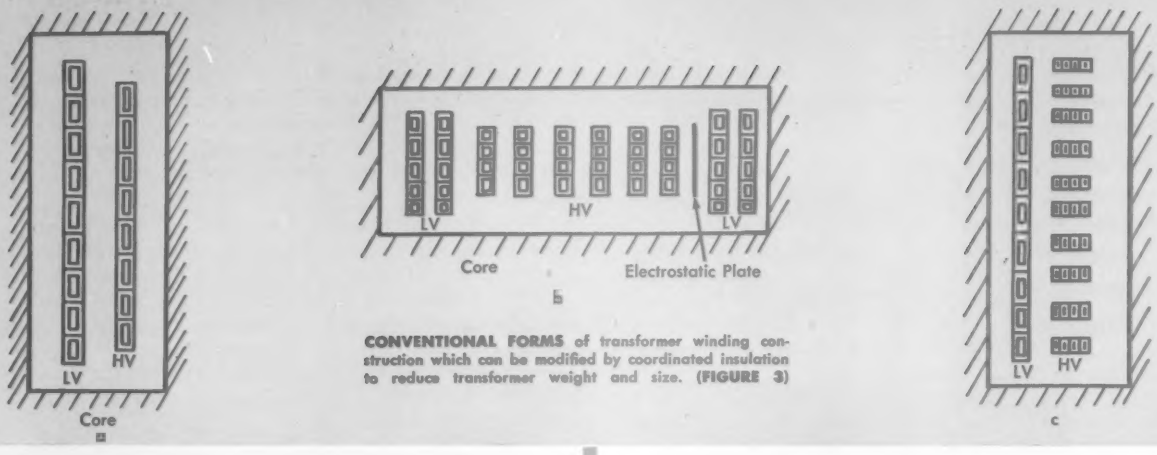



**VOLTAGE DISTRIBUTION** on a transformer winding during the initial or rising part of the surge is represented by the solid line. Deviation of actual voltage from the uniform distribution, indicated by broken line, is produced by capacitances of the winding. **(FIGURE 2)**

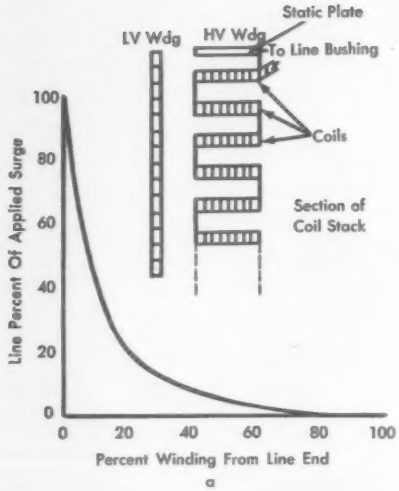
## Winding construction aids distribution

These conditions can have individual variations or improvements. Figure 4 shows three methods of varying the construction of a core type sectional winding to improve the voltage distribution near the line end. The coils can be spaced closer together at the line end than through the remainder of the winding (Figure 4b). This increases the capacitance between turns near the line end above that for the rest of the winding. If the voltage during the initial surge conditions is computed for this type of winding, it will be found that the voltage stress between turns in the closely spaced coils differs from the larger spaced coils. This scheme reduces the stress between line coils by distributing it further along in the winding. The turn stresses are relieved at the line end, where they are ordinarily the highest.

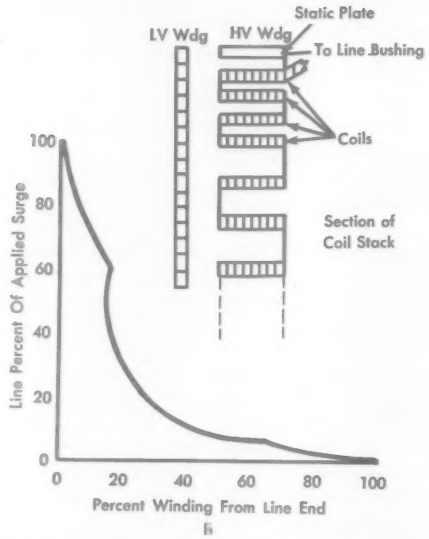
The scheme followed in Figure 4c recommends that line coils be made with wider and thinner conductor than the coils in the main body of the winding. This has the advantage of increasing the capacitance between turns near the line end without decreasing the capacitance between turns throughout the rest of the winding. The initial distribution of voltage on this type of winding will not have the marked discon-



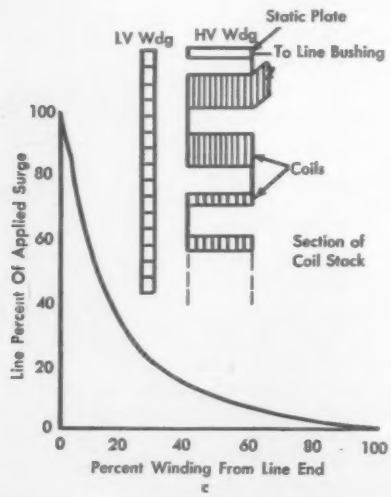

**CONVENTIONAL FORMS** of transformer winding construction which can be modified by coordinated insulation to reduce transformer weight and size. **(FIGURE 3)**



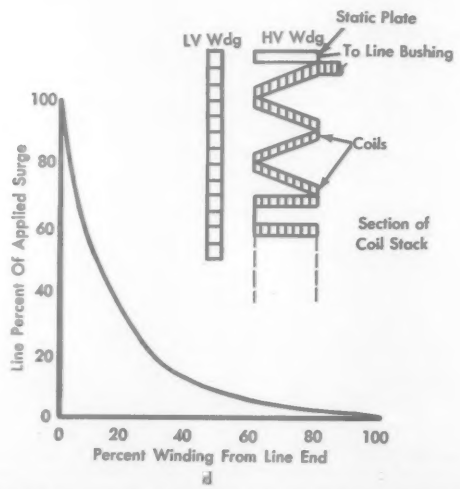

**TURN STRESS** in conventional core type windings where coils are spaced equally is higher near the line end of the winding. **(FIGURE 4a)**




**CLOSE SPACING** of line end coils distributes stress further along the winding and relieves turn stresses at the line end. **(FIGURE 4b)**




**WIDE CONDUCTORS** used on line end coils improve and stabilize voltage distribution between the turns near the line end. **(FIGURE 4c)**




**STAGGERED LINE** ends reduce voltage stress between turns on the line end. Same size conductors can be used for all coils. **(FIGURE 4d)**

tinuity of the previous scheme. Furthermore, it has a much better distribution between turns near the line end than the conventional scheme (Figure 4a).

The staggered coils in Figure 4d take advantage of the fact that the ends of the coils, which are connected together, have little voltage between them while the other ends have appreciable voltage. These coils will be spaced so that the open ends are approximately as far apart as conventional coils, but the series connected ends brought together with only enough spacing to allow for cooling. This arrangement also has the effect of increasing the series capacitance of the turns near the line end since parts of the coils are closer together than conventionally. The effect of this scheme is similar to that where the size of the conductor is changed. The voltage stress between turns on the line end is reduced, and has the added advantage of using the same conductor size for all coils. The turn-to-turn stress on the line ends can be reduced by these methods to the point where line end padding is not required.

After the crest of the surge is reached, the voltage is maintained for an appreciable time before it eventually diminishes to normal voltage. This results in an oscillation in the transformer. The condensers became charged during the initial surge and then immediately begin to discharge through the inductance. It has been found that the farther the initial distribution of voltage differs from a uniform condition (where the turn-to-turn stress is constant throughout the winding), the greater will be the magnitude of the induced oscillations, resulting in greater stresses between all parts of the transformer at later times. Figure 5 shows typical distributions for two types of windings.

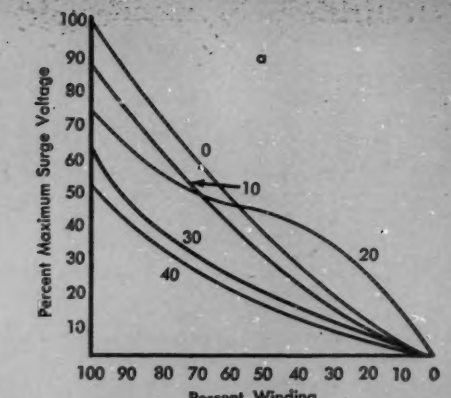
## Electrostatic fields stop creepage

When voltages throughout a transformer are known, the problem of insulating parts to withstand these voltages remains. A widely used conventional method of insulating transformer windings is shown in Figure 6. This method has been found from experience to be subject to creepage breakdown over the barriers or over the spacers between coils. To discover the causes for creepage breakdowns and to eliminate them, engineers turned to the principles of electrostatic fields.

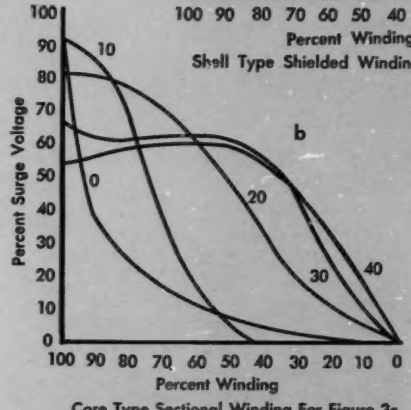
Figure 7 shows an electrostatic field about a square cornered electrode. The distance between the equipotential lines is an indication of the voltage gradient in the space between the square cornered electrode and ground. It can be observed that the equipotential lines are closer together near the corner than elsewhere in the space, and therefore the voltage gradient (volts per inch) is higher in this region than at other points in the space between electrode and ground. As the voltage on the electrode is increased, the corona breakdown of the oil will occur first in the highly stressed area near the corner.

The formation of corona in oil may not be serious since the oil will circulate to carry away the hot oil and replace it with new oil and so tend to prevent breakdown. However, if an insulating barrier of paper or some organic material is placed parallel to the ground and extending beyond the corner, the corona formed near the corner on the barrier will cause a surface breakdown on the barrier which can creep along the solid material until failure occurs.

One method of preventing such a breakdown is shown in Figure 8. A barrier is fitted around the corner so that it follows fairly close the lines of equipotential. This barrier

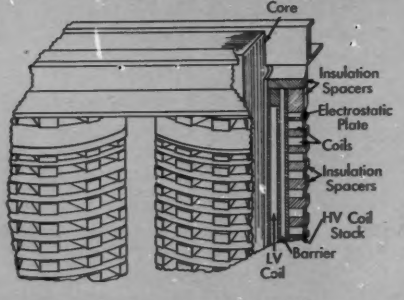



Shell Type Shielded Winding For Figure 3b



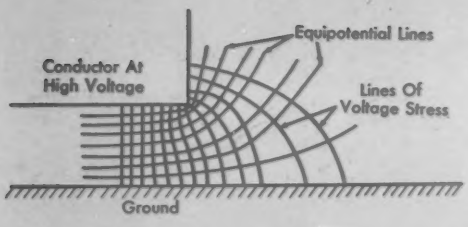

Core Type Sectional Winding For Figure 3c.

**NUMBERS ON CURVES** show surge voltage conditions on two types of windings in respect to time (microseconds) elapsing from start of surge until it passes through the transformer. **(FIGURES 5a and 5b)**

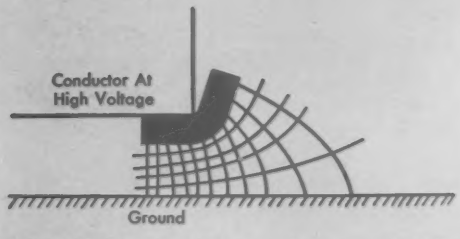



**CONVENTIONAL INSULATING** methods subject windings to creepage breakdown. Insulation strength is provided by oil spaces between coils and windings and supporting structures. **(FIGURE 6)**

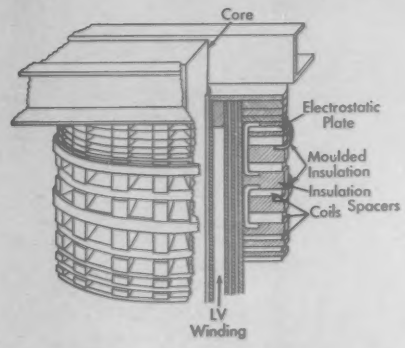
**SOLID INSULATION** required for proper coordination is moulded and dried by dielectric heat to fit transformer parts.




**NON-UNIFORMITY** of the electrostatic field around the corners often caused insulation failures in this type of assembly. **(FIGURE 7)**




**UNIFORM ELECTROSTATIC** voltage stress in this assembly indicates that solid insulation has provided additional strength. **(FIGURE 8)**




**LINE COILS** insulation of this sectional winding was coordinated to reduce transformer size by approximately 20 percent. **(FIGURE 9)**

will take up most of the high voltage stress of the field. The reminder of the assembly will then have a fairly uniform field.

If the dielectric strength of the material used near the corner is higher than the material in the rest of the space, the corona breakdown near the corner is prevented. This prevents any creepage failure. By the proper coordination of thickness and strength of this type of solid barrier, the insulation strength of the assembly can be increased considerably and creepage failures will be eliminated.

## Coordinated insulation cuts space

In order to apply this principle of insulating high stress points of individual assemblies throughout the transformer, it is necessary to know the points of high stress. Calculations made from surge test data show that the stresses are highest on the coil edges near the line terminal of the transformer. These edges must be protected by a high strength insulating material.

The best known material for high insulation strength in liquid filled transformers is paper impregnated with the liquid used. Therefore, the barriers used next to the coils should be made of paper and formed to fit the coils.

Varnished paper, moulded plastic, or other such materials are not suitable for this purpose, since they will not sufficiently increase the insulation of the assembly in the region of high stress to properly coordinate the assembly.

A method of moulding paper to fit the coils had to be developed to take advantage of the improvements offered by coordinated insulation. Several years of development have gone into the solution of the problem. Formerly, special-shaped collars, rings, etc. were built up from sheets of insulating paper glued together. However, this method allowed voids and breaks in the insulation destroying the effect of the solid, high strength material. By forming the insulation in dies under pressure and simultaneously drying with dielectric heat, almost any desired shape of conductor insulation can be obtained, absolutely free of voids and fitted exactly to the conductor contour.

Figure 9 shows a method of applying the principles of voltage stress reduction and of insulation coordination on a transformer winding.

This method of insulating can be used in a similar way to insulate the taps and leads on the terminal board. By insulating all leads with high strength paper and shielding bare parts from each other, the distances between parts can be reduced. If insulated parts are used, it is not necessary to place barriers between the leads or insulating tubes around leads, thus simplifying the transformer.

Since lightning surges are more severe than operating voltages, they will cause creepage more easily. A creepage failure may not occur on the first surge, but it may cause a burn which will be enlarged by successive surges until eventually breakdown will occur. The scheme of insulating corners to prevent creepage, therefore, allows the assembly to withstand any number of surges without failure.

## Smaller transformers are possible

Test results on actual units have proven this to be true. For example 138-kv transformers have been subjected to both steep front and standard full wave voltages, at test level, for a greater number of surges than are encountered in the normal life of a transformer with no evidence of corona. The full significance of this can be appreciated when it is realized that test voltages today are higher than those actually occurring on properly protected transmission lines. This leads to an obvious conclusion. *If the test voltage of this type of transformer were lowered to the level of service conditions, smaller transformers could be constructed.*

Such a transformer obtained by coordinating the knowledge of the behavior of lightning surges on transformers and the knowledge of insulation strength of parts, has many advantages. The cost of the transformer is reduced because of its lower insulation level. The efficiency may be increased and exciting current reduced for any capacity and operating voltage. This means reduced cost of transmission and generation equipment required to supply transformer exciting current and power losses. The reduced physical size of the unit also minimizes the size of handling equipment required for installation. Because of the fact that this scheme of insulation does not require end turn padding or excessive shielding and boxing of insulation, the cooling of the parts is improved considerably. Improvement in cooling reduces hotspot temperatures and results in added years of transformer service.

# Reheat

# PAST, PRESENT AND FUTURE

**Does reheat meet tomorrow's power plant economy needs? Look at its past achievements!**

C. A. ROBERTSON
Engineer-in-Charge
Test and Engineering Calculations Groups
Steam Turbine Department
Allis-Chalmers Mfg. Co.

RECENT surveys[1] disclose that over 70 percent of the country's power in the immediate future may be produced by steam turbine generator units. The millions of kilowatts of new equipment currently being installed or under construction provides substantial indication of the trend. Even more significant is the fact that many of the larger units under construction are designed for reheat cycle operation to offset rising fuel costs.

## Looking at reheat today

Simply speaking, "reheat cycle" today means that high pressure high temperature steam, after partial expansion in the turbine, is extracted at low or intermediate pressure, resuperheated in the boiler and returned to continue its flow through the turbine. An increase of four to six percent more of the total heat energy generated by the boiler is thus converted to useful work by the turbine[2] than would be possible without reheat.

Because of its more efficient fuel and steam utilization, the reheat cycle has been applied in approximately 20 utility stations in the United States since the first installation in 1924.

Experience with 65,000-, 80,000- and 115,000-kw tandem compound units installed in the last 18 years indicates not only an increase in thermal efficiency, but also an equal flexibility in performance of the reheat units as compared to the non-reheat turbines. Operating records of these regenerative reheat steam turbines have included base load and varying load operation, with frequent start-up and shut-down performance. Protective equipment in the reheat line has functioned reliably and modifications for succeeding designs relate primarily to details. The number of large new reheat units now under construction for high economy stations indicates that the reheat cycle is now being accepted as readily as the regenerative cycle was 25 years ago.

It is generally agreed that reheating is both economical and profitable for stations with high load factor and base load operation. However, there is some disagreement among engineers regarding justification of reheat for low load factor operation. But then high pressure, high temperature installations for low load factor operation have not been judged economical either.

## Reheating gained early recognition

Thermodynamic advantages of reheating steam were recognized and have been applied since the early days of the steam engine. The first known patent describing a method of steam jacketing cylinder walls to prevent condensation on inner cylinder walls was obtained by James Watt in 1769. Perhaps the first to use reheating by means of live steam coils in the receivers of compound engines was John Bourne. His application dates to 1859.

By the turn of the century, many compound engines, principally pumping engines, were equipped with reheaters. Published tests even describe the performance of an air compressor with four steam cylinders having three stages of reheating as well as four stages of regenerative feedwater heating. It appears that up to this time reheating was achieved by live steam.

In 1891, Parsons devised and patented a process of interstage live steam reheating in steam turbines by means of cored spaces in the diaphragms of a radial flow turbine. By 1900, a 1,000-kw Parsons tandem compound turbine was tested experimentally with externally fired reheat between cylinders. A 3,000-kw Parsons cross-compound geared turbine generator unit employing both reheating and regenerative feedwater heating was built in 1916, with reheating achieved by a waste heat reheat boiler[3]. Occasional development and application of reheating was conducted by European engineers up to the early 1920s, however only a small amount of performance information was published.

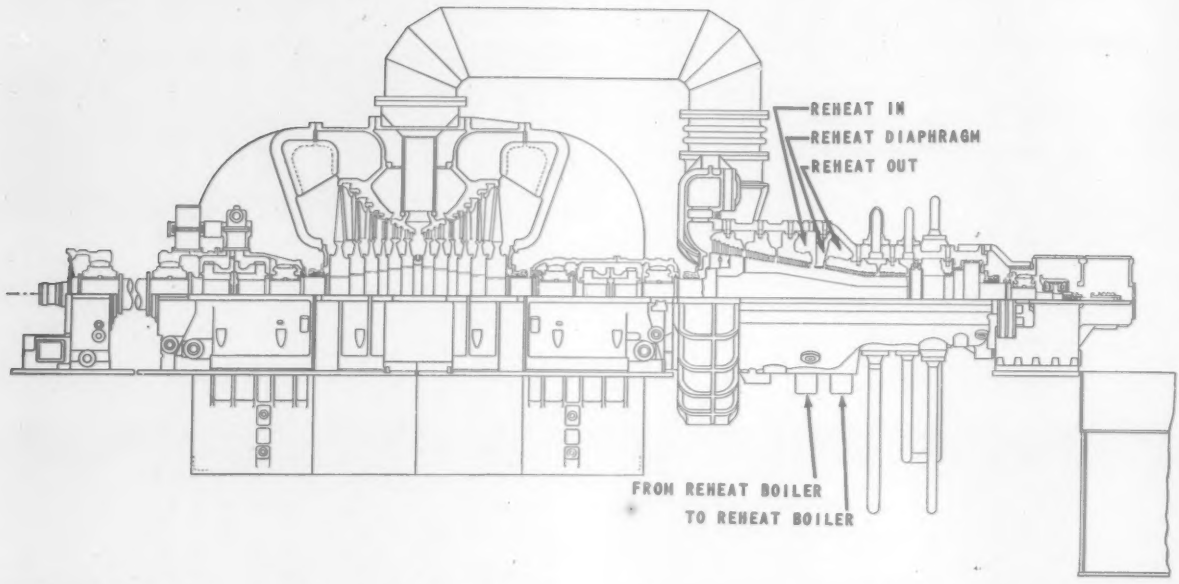
## Development of reheat cycle

From the start, steam turbine design has been guided by a constant desire to achieve higher machine economy which will result in lower plant fuel consumption. Improvements in turbine economy can be achieved by increasing throttle steam pressure and temperature, and by decreasing the back pressure at the turbine exhaust. Most of the attention was directed towards the raising of steam pressures and temperatures. This introduced new problems, one of which related to metallurgy.

About the time of World War I, steam temperatures had risen to the extent that excessive growth of cast iron cylinders occurred. Up to this time, cast iron was the chief ferrous material used for turbine castings.

Carbon steel castings replaced cast iron in high temperature parts, making possible the advancement of steam temperatures from 550 degrees F to approximately 700 degrees F by the early twenties. Steam pressures during this period were of the order of 200 to 250 psig.

Boiler design for high temperatures, especially superheaters, offered more difficulties than steam turbine design. The latter, therefore, kept pace with developments in steam generation.




**INTERSTAGE REHEAT** design used in the construction of the 80,000-kw reheat unit recently installed by a large midwest utility shows the unidirectional flow of steam through the high pressure cylinder. The actual turbine, as it appears in operation, is shown in the foreground on page 11.

Metallurgical knowledge of materials used in both boilers and turbines in the early twenties restricted steam temperatures to 700 or 750 degrees F. Consequently, increasing steam pressure was the only alternative if economy was to be improved further.

Analyses were made at this time to determine the possibility of raising steam pressures. The results indicated a maximum of 350 to 400 psig for 700 to 750 degrees F steam temperatures without increasing the moisture content at the exhaust above the accepted safe value of 10 to 12 percent. Moisture at the exhaust causes erosion of low pressure exhaust blading together with loss of efficiency. The degree of erosion is somewhat proportional to the amount of moisture, an effect which increases with blade speed.

The 350 to 400 psig pressures became standard during the early 1920s for straight condensing or regenerative turbine cycles. However, studies were conducted for advancement to still higher pressures, 600 and 1,200 psig. This effort was stimulated by the possibilities of still greater thermodynamic gains. As previously mentioned, these pressures would also result in excessive moisture content at the exhaust.

Reheat appeared to be the logical solution with steam temperatures limited to 700 to 750 degrees F range because it had several advantages:

1. Reheat improves economy by increasing available energy.
2. Reheat increases the enthalpy at exhaust, resulting in lower moisture.
3. By reducing moisture at exhaust, fewer stages operate in the wet field and with less moisture. Stage efficiency is highest when operated with dry or superheated steam.
4. Reduction of moisture also proportionately reduces blade erosion at the exhaust.

Recommendations for the range of steam pressures to be used created two schools of thought during this speculative period. One maintained that the range of pressure should be limited to about 600 psig, the other favored increasing pressures to 1,200 psig.

## Reheat installations in 1920s

First large-scale regenerative reheat turbines of 40,000 and 60,000 kw for steam at 600 psig and 725 degrees F were installed in 1924. These turbines were, respectively, single cylinder with reheat between stages and cross-compound with reheat between cylinders. Both installations employed separate reheat boilers. The first was in the Philo station of Ohio Power Company, the latter was in the Crawford Avenue station of Commonwealth Edison Company.

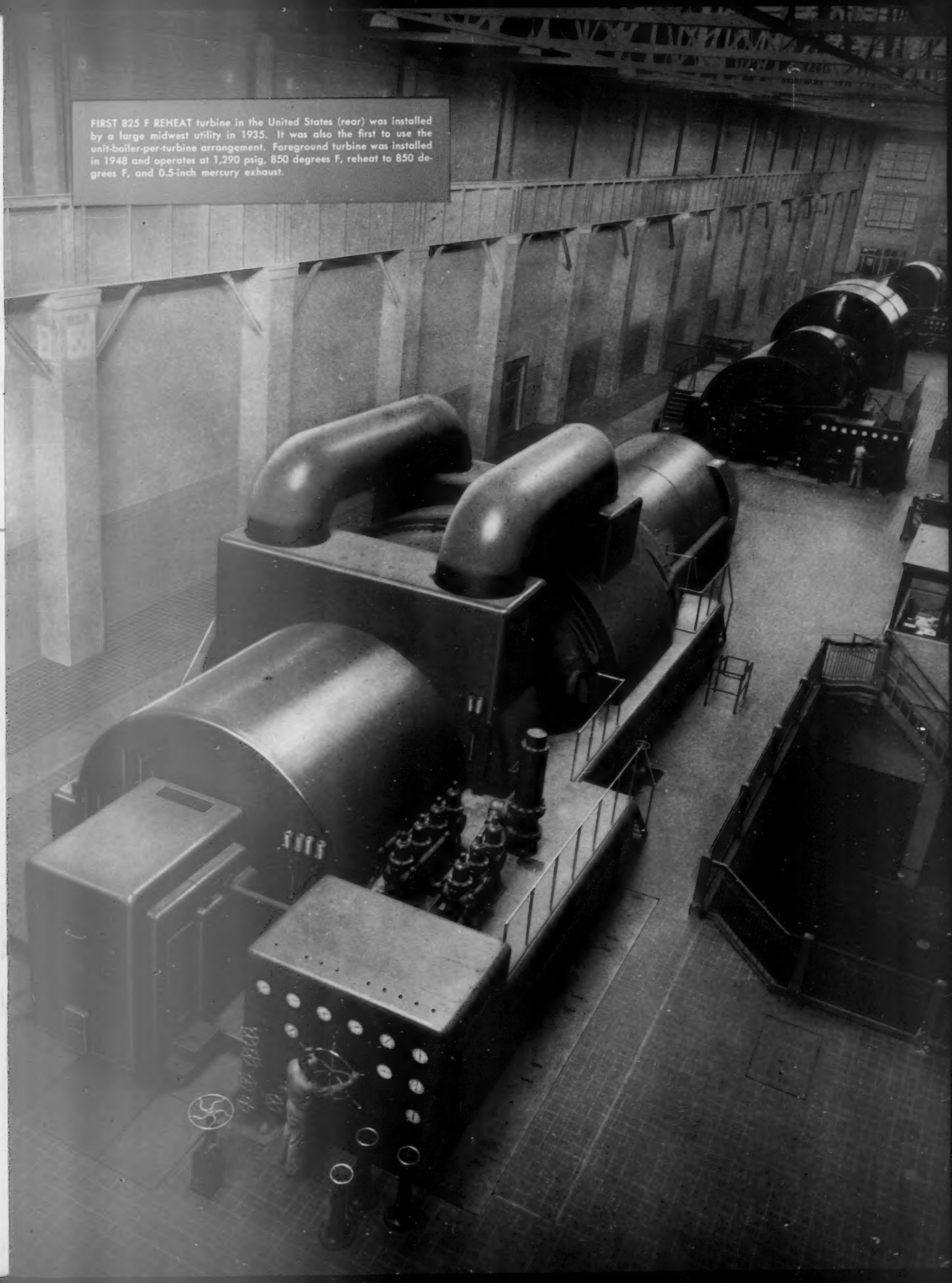
High pressure reheat installations of the 1,300 psig type were first put into service in 1925 and 1926. The first of these was accomplished by adding a 3,360-kw topping unit at the Edgar station of the Boston Edison Company, and the second was the first of four 7,700-kw topping turbines at Lakeside station of the Wisconsin Electric Power Company.

Exhaust steam in these installations was resuperheated in the reheater, an integral part of the high pressure boiler, for further expansion in low pressure units. Approximately six stations in the United States are using topping reheat turbines at the present time, with twelve turbine generator units involved.

Cross and tandem compound turbines of both 600 and 1,300 psig classes were in operation, or being installed in 1930. These utilized boiler reheat, steam reheat or a combination of both.

## Reheat turbines mature

Judged by present day standards, the most important reheating development relates to the two general types of turbines presently under construction: tandem compound turbines with reheating between stages in the high pressure cylinder and cross compound type units with reheat between cylinders.



FIRST 825 F REHEAT turbine in the United States (rear) was installed by a large midwest utility in 1935. It was also the first to use the unit-boiler-per-turbine arrangement. Foreground turbine was installed in 1948 and operates at 1,290 psig, 850 degrees F, reheat to 850 degrees F, and 0.5-inch mercury exhaust.

The early tandem compound turbines with reheating between stages in the high pressure cylinder were the 65,000-kw and 115,000-kw turbine generator units for the Public Service Company of Northern Illinois, at Waukegan, installed in 1930 and 1931, respectively. Steam flow was uni-directional through the high pressure cylinder.

About 29 reheat steam turbine generator units of various condensing types were installed between 1924 and 1932. Twenty of these were of the 600 psig, 725 degrees F class, and nine were of the 1,300 psig, 725 degrees F category.

The first 825 degrees F reheat steam turbine generator unit was installed in 1935 at the Port Washington station of the Wisconsin Electric Power Company. It was an 80,000-kw unit and now operates with steam conditions of 1,230 psig, 850 degrees F, reheat to 850 degrees F, and 29½-inch referred vacuum. This tandem compound turbine, with reheat between stages in the high pressure cylinder, was the first installation to use the now accepted one-boiler-per-turbine arrangement in which the reheater is an integral part of the boiler, simplifying reheat temperature control.

The Port Washington installation also represented the first of five units, three of which are in operation and two under construction. This station has continued to establish outstanding records for efficient performance.[4]

Only three reheat turbine generator units were installed in the United States from 1932 to 1941. These were Port Washington No. 1, 80,000 kw; State Line No. 2, 150,000 kw; and Powerton No. 4, 105,000 kw.

## Non-reheat period—1932 to 1941

Advancement of metallurgical knowledge and experience in the 1930s permitted increases in initial steam temperature through the use of alloy steels and allowed raises in steam pressure to 1,300 psig without exceeding recognized limits of moisture at the exhaust. This accomplished one of the factors which led to reheating and resulted in the installation of a large number of non-reheat plants. Use of non-reheat topping turbines in the late thirties, although limited in application, provided gains in station economy.

Opinion was divided between the use of a simple plant without reheat or the continuation of reheat with its higher thermal efficiency and cost. However, with the rising cost of fuel, and in spite of the advent of still higher pressures and temperatures, the reheat cycle is again gaining favor.

Another noteworthy development of reheat turbines has been their successful application for ship propulsion service as well as for central station service.[5]

## Reheat returns

Since 1941, reheating has returned for a large number of units for initial temperatures of 900 to 1050 degrees F with initial pressures from 1,380 to 2,300 psig. These represent the present day renewal of interest in the reheat cycle because of the improvement in plant economy and increasing fuel costs.

The trend toward reheat today involves tandem compound units from 40,000 to 100,000 kw, with reheating between stages of the high pressure cylinder and cross compound types of the order of 125,000 to 150,000 kw.

A further step in the direction of higher economy, where condensing cooling water temperature permits, may be to use vacuum lower than one inch absolute. Reheat will serve a very useful purpose for such installations by reducing the potentially higher than usual moisture at the exhaust.

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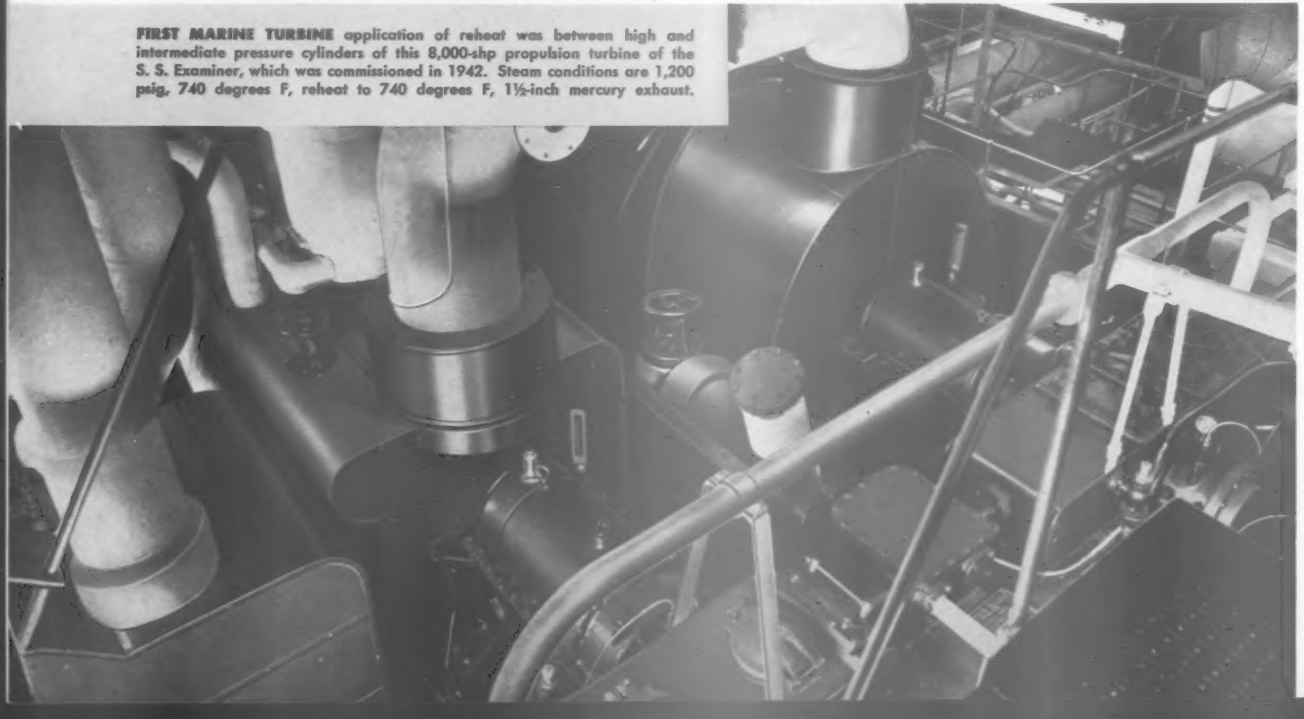


**FIRST MARINE TURBINE** application of reheat was between high and intermediate pressure cylinders of this 8,000-shp propulsion turbine of the S. S. Examiner, which was commissioned in 1942. Steam conditions are 1,200 psig, 740 degrees F, reheat to 740 degrees F, 1½-inch mercury exhaust.

FRASER JEFFREY
Assistant to Chief Electrical Engineer
The Allis-Chalmers Mfg. Co.

# Care of AC Rotating Equipment

PART ONE OF FOUR PARTS

**Familiarity with equipment, its use and needs, is essential for effective maintenance.**

INTELLIGENT and consistent maintenance of electrical machines powering industries is more important today than ever before in the history of manufacturing. Intelligent upkeep or repair is most important because greatly increased production requirements demand that machines be at optimum efficiency at all times. Worn-out equipment cannot be replaced readily. Even if quick replacement were possible it might mean denying vitally needed materials to some other phase of industry. Also, supplementing existing facilities with additional equipment to increase production of essential materials at such times is another difficulty hard to circumvent.

## Knowing "hidden things" is important

Too much stress can not be placed on the importance of maintenance and how it is frequently possible to greatly improve the quality and permanence of the work done by a better understanding of many hidden and unseen things that cause failures of electrical equipment. If the cause of the trouble is thoroughly understood, it is self-evident that more effective corrective measures can be taken than would otherwise be the case. In many installations the difficulties might be due to improper application, power instability, transient conditions, switching, the so-called "inching" of machines and other improper operating conditions. If such things are known, a much more intelligent approach to the proper corrective measures is assured.

Maintenance is chiefly concerned with continuity of production through upkeep and repair.* Since the former often eliminates the need for repair, it will be stressed because of its preventive contribution.

Preventive maintenance deals with routine cleaning and inspection of equipment. These considerations should be scheduled according to the type of equipment, nature of application, location, production schedule, etc. Some machines need hourly or daily inspection, others may require semi-weekly or weekly attention. However, schedules should be prepared so that important equipment is given the most frequent and detailed care.

*Machine repair will be discussed in later installments.

**DUST IS DANGEROUS!** Although this stone quarry motor is built to operate under such adverse conditions, an accumulation of abrasive dust constitutes a serious hazard. **(FIGURE 1)**

## Don't overlook dusting

Dirt and dust are encountered in most installations. A maintenance man could be justly charged with negligence or sabotage if he would encase the heat dissipating surfaces of vital electrical machines carrying full load with a layer of heat insulating material. Allowing dirt and dust to settle on such equipment (Figure 1) amounts to the same thing. Both are enemies of insulation and lead to higher than normal machine temperatures which, in turn, hasten insulation deterioration.

Fortunately, dirt and dust can usually be removed from exposed parts by specially built vacuum cleaners or can be blown from exposed machine parts by clean, dry compressed air. Air pressures generally used vary from 40 to 60 psi. However, the pressure used for a specific job should be adjusted for ready dust and dirt removal without damage to the winding and insulation. In equipment where dust and dirt become solidly packed in ventilating apertures, etc., and cannot be removed by blowing, it is best to take the machine apart and clean small openings or parts with bottle brushes.

## Stray oil complicates dirt problem

Oil mixed with dirt and dust (Figure 2) provides an extremely undesirable and harmful combination. Grimy or greasy insulation usually has to be wiped from the surface of coil ends, etc., with a cleaning agent which may be a solution of 60 percent carbon tetrachloride and 40 percent varnish makers' naphtha, or ordinary gasoline without lead compounds. Pure carbon tetrachloride is not recommended because of its deteriorating action on varnishes and its extremely harmful toxic effects. No amount of wiping or cleaning can remedy a situation where insulation is badly oil-soaked. Depending upon the importance of the machine, it is usually advisable to install new coils.

In cleaning machines it is important to include such vital parts as brush holders and slip or collector ring insulations where surface creepage along such dirt ridden

**OILY GRIME** presents about the worst operating conditions for any motor. Fortunately, motors are able to cope with circumstances like these. Frequent and constant watching provides added protection against oil seepage. (FIG. 2)

**FLOODS SPIRAL** maintenance and operating costs. Water, silt and other contaminations require careful washing and drying of all equipment before any of it can be used again. (FIGURE 3)

parts often takes place. Oil-soaked brushes should be replaced with new ones.

## Check moist insulation frequently

Moisture-soaked insulation is unhealthy insulation. This condition usually results when machines are stored in damp locations, allowing moisture-laden air to carry water into a machine not built for such operation, or machines that have been actually submerged, as shown in Figures 3 and 4. Driving moisture from the windings of such machines requires special treatment.

Frequently, foreign matter deposits have to be washed away with clean water at a low hose pressure varying from 40 to 60 psi. However, pressure used for a specific job should be adjusted so that the dirt and other foreign matter can be removed without damage to the winding and the insulation.

## Drying moist insulation

Heating ovens can be used when a large number of small machines are involved. Where ovens are not available, machines can be covered with a canvas or housing in which stoves or heaters supply the necessary heat to drive out moisture from the windings.

There are several methods of drying rotating electrical machines. Slip ring induction motors, for example, can be dried by alternating current with the rotor in the stator. Slip rings should be shorted and the rotor blocked to prevent it from turning. By supplying a suitable current at low voltage the rotor and stator can be baked out simultaneously. Temperature for most baking conditions should not exceed 75 to 80 degrees C, as measured by thermometers, thermocouples or resistance units located in the hottest spots available. If the driving end of the prime mover equipment such as a steam turbine, etc., is able to operate the electrical end, provided the rotating member has already been dried out, the stator can also be dried out by running at either reduced or full speed, the stator windings being short-circuited, and the field regulated to obtain such currents that temperatures of 75 to 80 degrees C are not exceeded.

Direct current can also be used for drying stators and rotors of slip ring type induction motors, stators of synchronous motors, synchronous condensers, and a-c generators. Preferably, the current should be equal in all parts of the winding. Machines with both ends of the phase windings brought out, such as leads and neutral points, are easily handled, if direct current is available.

Direct current is also recommended for drying out the stationary element carrying the field coils of a rotary converter, the rotating element carrying the field coils of a synchronous motor or condenser, a definite pole a-c generator, or a turbo-generator. Direct current is recommended because:

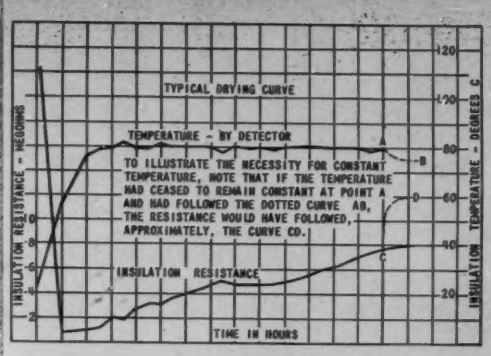
1. Alternating current used in the windings of the field coils of such machines for drying them out will cause circulating currents in the damper windings and may result in dangerous overheating, if and when such windings are used.
2. Due to the inductance of such windings, an alternating current voltage considerably in excess of the normal direct current voltage operating potential might be required to force the proper amount of current through the winding for baking purposes. As such, it could easily cause a breakdown of the winding insulation.
3. In some cases, eddy current losses in adjacent iron structures might cause localized heating.
4. Direct current can be more easily and readily controlled for such specific applications.

## Measuring insulation resistance

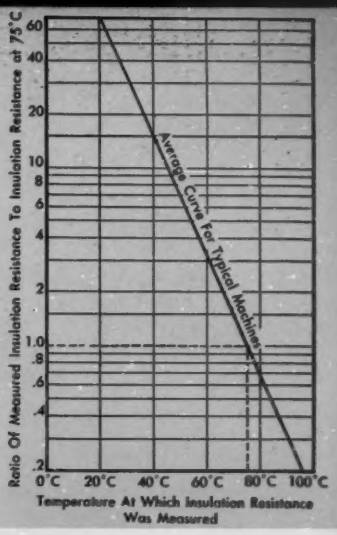
When a machine is very wet or has been immersed in water, very special care has to be exercised, after the foreign matter deposits have been washed away because the coil insulation might be broken down or punctured by improper application of the megger itself. In such cases, the windings should be given a thorough baking out over an extended period of time. When it is felt that the insulation is in fair condition, the insulation resistance should first be measured using a low voltage source until it is indicated that the treatment of the winding shows that a suitable megger can be used.

A low reading megger, ranging from 1 to 300 megohms and possibly 500 volts, is frequently used for measuring insulation resistance. Measurements should be made at about 75 degrees C, if such is the temperature of the bake-out. Although the insulation resistance of a cold winding may show infinity, it may be very low when heated up to 60 to 75 degrees C, as shown in Figure 5. One thing to remember, however, is that successive readings to check insulation resistance should be made at the same temperature since considerable variations will be obtained when readings are taken at different temperatures (Figures 5 and 6).

**SEEMINGLY USELESS,** this silt, pebble covered motor can be reconditioned for use through maintenance "know how." This is not true in all such cases. **(FIGURE 4)**


TYPICAL DRYING CURVE
TEMPERATURE - BY DETECTOR
TO ILLUSTRATE THE NECESSITY FOR CONSTANT TEMPERATURE, NOTE THAT IF THE TEMPERATURE HAD CEASED TO REMAIN CONSTANT AT POINT A AND HAD FOLLOWED THE DOTTED CURVE AB, THE RESISTANCE WOULD HAVE FOLLOWED, APPROXIMATELY, THE CURVE CD.
INSULATION RESISTANCE
TIME IN HOURS
INSULATION RESISTANCE - MEGOHMS
INSULATION TEMPERATURE - DEGREES C

**TYPICAL DRYING OUT** curve used for recording insulation resistance of larger machines. Successive measurements should be taken at the same temperature. **(FIGURE 5)**


Ratio Of Measured Insulation Resistance To Insulation Resistance at 75°C
Average Curve For Typical Machines
0°C 20°C 40°C 60°C 80°C 100°C
Temperature At Which Insulation Resistance Was Measured

**INSULATION RESISTANCE** readings taken at different temperatures vary, as illustrated by the average curve for typical machines plotted at right. **(FIGURE 6)**

Another important requisite is that the megger be cranked at full speed until a stable reading is obtained. Usually, a 1,000-volt megger is used for high voltage machines. Larger machines should be tested with a motor driven megger which is cranked until a constant reading is obtained, usually requiring 10 or more minutes to attain desired results.

## Dryout time varies

The time element required to dry out a winding cannot be predetermined. The larger the machine, the more time is required, especially on large high voltage units having thick insulation walls. For such cases, it is advisable to plot the points in curve form (Figure 5). It should not be necessary to continue the process after the insulation resistance becomes constant for three to four hours on small low voltage machines and 12 to 24 hours or more on large high voltage machines.

Insulation resistance values obtained by this method apply to the embedded portion of the coils. It is assumed that when the resistance is satisfactory for the embedded section, it is also satisfactory for the end portions. However, on high voltage machines, say 25,000 kva, 13,800 volts, it is sometimes advisable to continue to bake out for a further limited period of time, 24 hours or more, in order to decrease the possibilities of corona action.

## Accurate calculating difficult

Calculating insulation resistance of a dry winding with any degree of accuracy is by no means easy. Report 43, December, 1946, of the "AIEE Recommended Practice for Insulation Resistance Testing of A-C Rotating Machinery", contains proposed formulas which may be used as a guide in calculating the approximate minimum insulation resistance. Equation 1 shows minimum insulation resistance for a-c rotating electrical machines 1,000 kva or above.

$$R_1 = Sk_s f \frac{E + 3600}{\frac{kva}{30} + 200}$$

Where

$R_1$ = Minimum insulation resistance of armature or stator winding in megohms measured at 500 volts direct current after one minute. (The test is made with all windings of the same voltage rating connected together.)

$E$ = Rated voltage of the machine.

kva = Rated kilovolt amperes of machine.

$S$ = Machine speed constant as follows:

| Speed (RPM) | S |
|---|---|
| 3600 | 1.3 |
| 1800 | 1.0 |
| 1200 | 0.9 |
| 600 | 0.7 |
| 100 | 0.4 |

$k_s$ = Insulation class constant
= 1.0 for Class "B"
= 0.10 for Class "A"

$f$ = winding temperature constant (winding temperatures obtained by embedded detector)

| Class "B" Insulation | | Class "A" Insulation | |
|---|---|---|---|
| f | Temp. °C | f | Temp. °C |
| 1.0 | 75 | 1.0 | 75 |
| 2.6 | 50 | 6.9 | 50 |
| 6.9 | 25 | 47.0 | 25 |

Equation 2 gives the minimum insulation resistance of a-c machines below 1,000 kva.

$$R_1 = \frac{E + 1000}{1000}$$

Where $R_1$ = Minimum insulation resistance in megohms measured at 500 volts d.c. after one minute.

$E$ = Rated voltage of machine.

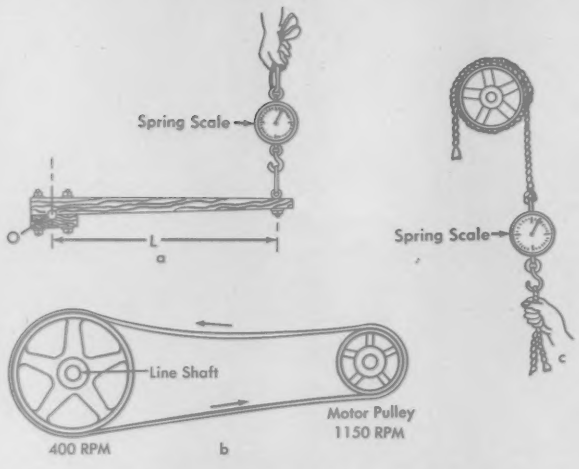
In instances where dirt and dust, stray oil and wet insulation are encountered, a coat or two of good air drying varnish should be applied to the stator coil ends after the machine has been cleaned and dried out. Spraying is preferred to brush application.

## Corona deteriorates insulation

Corona deterioration of insulation on windings of electrical equipment is often evident where machine potentials exceed 10,000 volts. It is usually indicated by white spots on the sides of coils or leads where they emerge from the iron or where they are close to each other.

Corona discharge in air causes reactions between its component elements and organic materials such as varnish, cotton tapes, cords, etc., are attacked and deteriorated by oxidation action of the ozone and by the action of nitric and nitrous acid formed by the oxygen and nitrogen combining with moisture in the air.

**IMPROPER APPLICATION** of equipment invites breakdown and loss of production. Knowing the "hidden things" of machine upkeep would have recommended replacement of this poor motor drive arrangement. **(FIGURE 7)**




**STATIC TORQUE** conditions of a driven load can be determined accurately by the above methods. However, several readings should be taken, preferably after equipment has been idle for some time. **(FIGS. 8a, 8b and 8c)**

Corona spots should be examined carefully to see that the insulation has not deteriorated. Spots where corona damage is evident should be repaired and the manufacturer of that particular equipment should be consulted regarding possibilities of changes to eliminate the corona discharge. As a first aid, corona action may be arrested by filling all air pockets of affected areas with insulation material.

## Bearings need particular care

Instruction pamphlets supplied with electrical machines should be kept handy. The information they contain on bearings should be carefully observed.

For instance, oil should not be added to the reservoir of a sleeve type bearing while the machine is running because it is unlikely that the sight gauge will give a proper reading of the true oil level. Due to rotation, the oil ring tends to pile up oil on one side of the oil reservoir and lower it on the other. Oil rings must be free and continually turn with the shaft. If for any reason the oil ring travels to one end of the slot in the bearings and hugs that end, the maintenance man or operator should realize that something is wrong and should investigate.

Another common mistake is the filling of bearings daily. In addition to being wrong, it is dangerous. The excess oil or grease has to go somewhere and usually finds its way to the windings and into the machine.

Excessive chain or belt tension often causes overheating of bearings. Frequently, it can be remedied by reducing the tension or by rearranging the drive so that the slack side of the belt can be changed to the top instead of the bottom. Bearings also tend to overheat when pulley centers are too short, pulley diameters are inadequate, belt speed is too high, etc. (Figure 7.)

## Minimize static bearing friction

High speed motors are frequently supplied with oil rings and forced lubrication. Large, heavily loaded bearings should be supplied with some form of pressure lubrication to actually "lift" the shaft from contact with the bearing babbitt. This facilitates starting and reduces the danger of pulling the babbitt in the bearings. Ordinarily, lifting reduces static torque, but is not used to maintain bearing life. Many machines can be turned by hand if oil pressure lifting is used properly and the problem is not complicated by other frictional and static inertia conditions.

In the case of flywheels, motor-generator sets or other equipment having large masses rotated between bearings, the power to overcome bearing friction at the time of starting may be estimated from Equation 3:

$$\text{Synchronous Hp} = .300 \times W'' \times \frac{r}{12} \times \frac{2\pi \times \text{RPM}}{33{,}000}$$

Where Synchronous Hp = A convenient reference of the measurement of torque expressed in horsepower at synchronous speed rather than in pounds at one-foot radius.

$W''$ = Weight in pounds of rotating parts.

$r$ = Radius in inches of shaft in bearings.

RPM = Synchronous speed of motor.

The coefficient of static bearing friction in equation 3 is taken as 0.30, but variations in conditions may make it advisable to change the value. As given, 0.30 is intended to cover starting under "average" conditions. It does not apply to ideal conditions, such as oil pressure sufficient to raise the shaft, etc., or extreme conditions of bearing loading when the shaft rests directly on the bearing babbitt.

The coefficient of friction for bearings raised from partial or full contact with the babbitt by oil pressure will drop from 0.30 to a value varying, in some cases, from a low of 0.010 to a high of 0.022, or an average of 0.016.

## Spring balance calculation practical

A dependable estimate of the "static" conditions of a load may also be obtained by using a spring balance at a known radius. Suppose it is desired to learn the static conditions of a long line shaft in a factory. A spring balance attached by a rope around a pulley of known diameter, or to a beam rigidly attached to the shafting, will indicate the desired condition.

In cases of this sort, several readings under the most unfavorable conditions are recommended. For instance, static torque on a line shaft should be taken preferably before starting operation on Monday morning, after the shafting has been idle over the weekend. Also, the readings should be taken under minimum temperature conditions, i. e., at a time that will simulate starting under the lowest temperature likely to be encountered. When readings are taken, the beam should be at the horizontal position, Figure 8a. The torque value for this condition is expressed in Equation 4, as follows:

$$T = \frac{W - w}{16} \times \frac{L}{12}$$

where T = Torque in pounds at one-foot radius.

L = Length of beam in inches from center of shaft to point of pull of spring balance.

w = Weight in ounces of the beam when free to rotate from the center.

W = Weight in ounces read on spring balance for any given load.

When static torque has been determined, it can be translated into synchronous horsepower by using Equation 3, thus solving one of the important application problems. Synchronous horsepower can be defined as a convenient reference of the measurement of torque expressed in horsepower at synchronous speed rather than in pounds at one-foot radius.

Since the motor speed often differs from the driven machine speed, care should be exercised when using the formula. As an example, consider an arrangement similar to Figure 8b where a line shaft runs at 400 rpm and the motor operates at a speed of 1,150 rpm. If the value of "T" is ascertained by using a beam on the line shaft, the synchronous horsepower is determined from equation 5, by using 400 as the rpm value:

$$\text{Synchronous HP} = \frac{T \times 2\pi \times RPM}{33{,}000}$$

where T = Torque in pounds at one-foot radius.

RPM = Normal speed in rpm of shafting or part for which the pull is measured.

If, on the other hand, a beam is not used on the motor shaft, the value of rpm used in the horsepower formula is 1,150, not 400. Each method checks the other. If a rope is used around a pulley, as in Figure 8c, the torque formula, while practically the same, considers slightly different conditions, as shown in Equation 6:

$$T = \frac{W \pm w - w'}{16} \times \frac{L}{12}$$

where L = Length in inches from center line of pulley to center line of rope.

w = Weight in ounces of the length of rope on the spring release side. (This is a plus quantity if the measurement is made vertically downward, and a minus quantity if measured vertically upward.)

W = Weight in ounces read on spring balance for any given load.

w′ = Weight in ounces of the free length of rope.

These methods provide the means of determining whether or not a certain motor has the necessary torque to break away and start any given load. If it were determined, for instance, that the synchronous horsepower to break away was 1½ to 2 times the motor rating, it is obvious that that particular motor, were it a squirrel-cage induction machine, would undoubtedly not be capable of exerting this large amount of static torque unless it were specially designed and built for it.

## Watch bearing clearances

Bearing clearances in sleeve type bearings should not be excessive, otherwise the rotor may rub the stator iron and short circuit the punchings in machines having small air gaps, like induction motors. Localized hot spots may develop and cause serious lamination and insulation damage. A rough rule for clearance of sleeve type bearings and shafts is .0010 inch for each inch diameter of the bearings.

Ball or roller bearings require maintenance which differs from that for sleeve type. Ball or roller bearings should not be packed with excess oil or grease, for, if they are, the bearings are bound to overheat at fairly high speeds. Such bearings require very little attention, but should be kept clean at all times. This problem is further simplified because manufacturers' instructions definitely include the quantity and type of oil or grease best suited for proper lubrication. It is not uncommon to obtain successful operation at extreme speeds by lubrication with atomized oil.

## Check alignment and thrust provisions

Solid couplings should be checked with feelers before being assembled. Even flexible couplings should be carefully aligned if maximum operating life is desired. In general, couplings, pulleys, pinions, etc., should be checked for misalignment at the time of installation, as well as during the period of service.

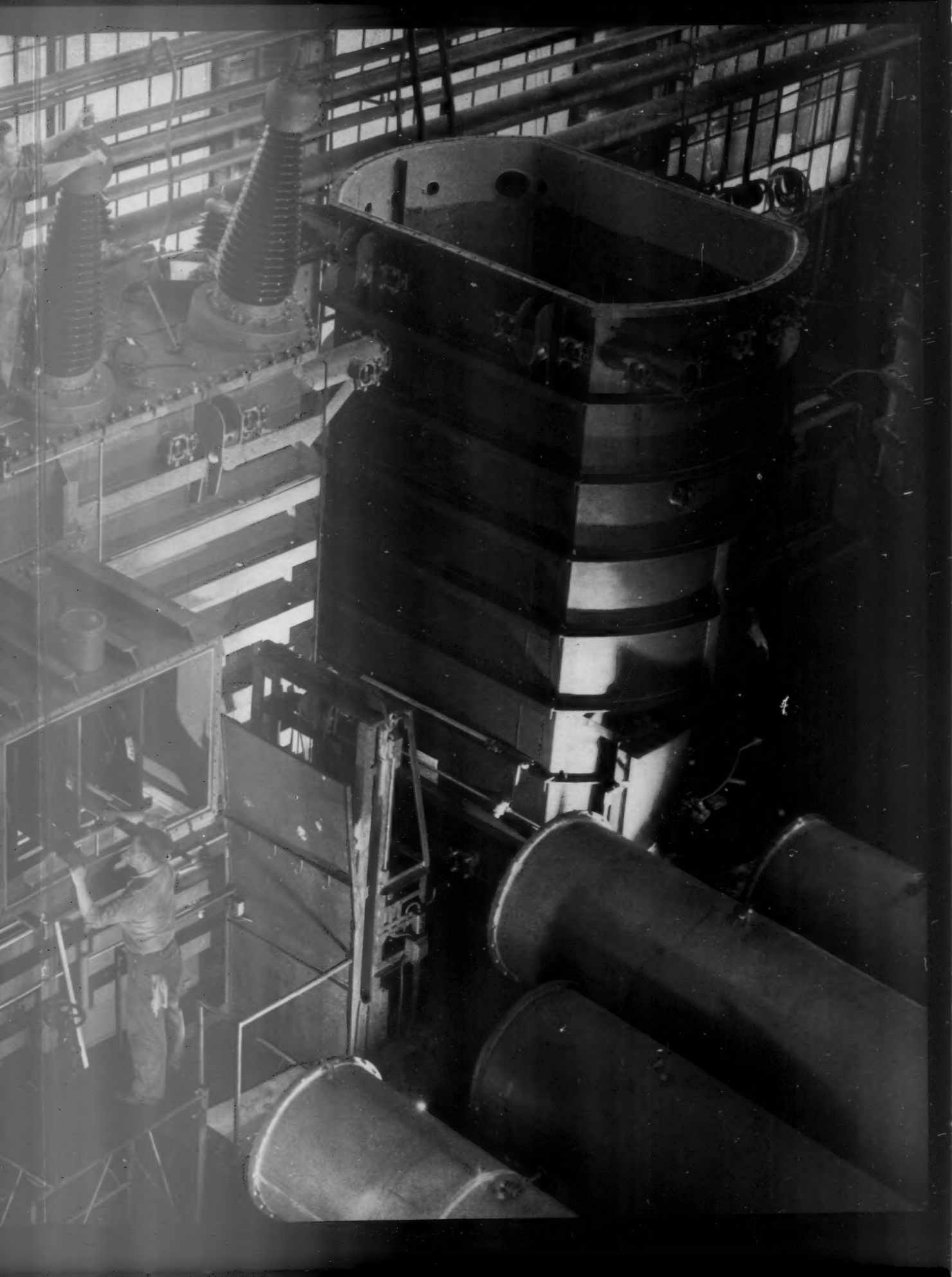
Ordinarily, motors will absorb a small amount of thrust. A thrust bearing or special thrust surface or surfaces on bearings of the equipment producing thrust are recommended for larger amounts of thrust. Sometimes, as might be the case with vertical induction motor driven pumps, provision for thrust is made in the motor bearings.

That a motor will absorb all the thrust should never be taken for granted. If it is known that thrust will develop, care should be taken in the alignment and set-up so that it will be absorbed by the proper thrust bearing surface, rather than by the surfaces of the motor bearings which may not have been designed for such use.

Because it has its roots in installation, application and operation of machines, maintenance is a science, not a mere task. Being able to detect the source of trouble and understanding the "hidden" factors result in more effective corrective measures which, in turn, favorably affect the life of equipment. The maintenance man should be familiar with not only what to do but, more so, with why and how these conditions occur and how they can be best remedied.

*Next installment will cover vibration and effect of overloading on insulation.*

**LARGE TRANSFORMERS,** like this 30,000-kva, 3-phase power unit under construction for a midwest utility, are helping power companies to meet tremendously increased industrial and home demands for electricity. Man at top is putting terminal caps on one of three 138,000-volt high voltage bushings. The other is tightening connections for load ratio equipment.

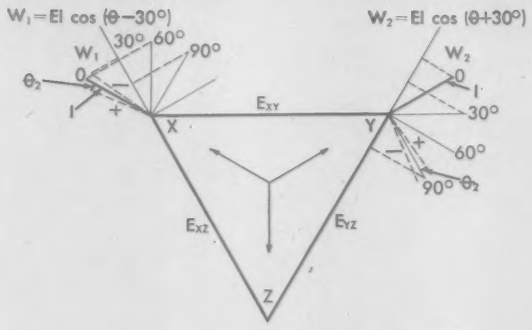


# Correcting Errors in 3-Phase Power Measurement

D. R. LAIB
Allis-Chalmers Mfg. Co.
Pittsburgh, Pa.

**Ratio and phase angle errors—how to correct them.**

WHEN current and potential transformers are used in the circuit to be measured, two sources of errors occur in each transformer. These must be considered if precision is required. There is an error in ratio which causes the secondary voltage (or current) of the instrument transformers to differ slightly from the marked nameplate rating. There are also phase angle errors which are a measure of the difference in time relation of the secondary voltage and current from the primary voltage and current. These errors are inherent in instrument transformer design and exist because a portion of the input energy is required to excite and supply the losses of the magnetic circuit. There is also an $I^2R$ loss due to the ohmic resistance of the windings. This difference in volt-ampere input of the primary circuit and the useful volt-ampere output of the secondary circuit, including the connected burden, is translated in terms of ratio and phase angle errors.




| 3-Ph PF | | $W_1$ PF |
|---|---|---|
| 100% PF | $W_1=EI\ Cos-30°$ | +86.6% |
| 86.6% PF | $W_1=EI\ Cos\ (30°-30°)$ | +100% |
| 50% PF | $W_1=EI\ Cos\ (60°-30°)$ | −86.6% |
| 0 PF | $W_1=EI\ Cos\ (90°-30°)$ | −50% |

| 3-Ph PF | | $W_2$ PF |
|---|---|---|
| 100% PF | $W_2=EI\ Cos+30°)$ | −86.6% |
| 86.6% PF | $W_2=EI\ Cos\ (30°+30°)$ | −50% |
| 50% PF | $W_2=EI\ Cos\ (60°+30°)$ | 0 |
| 0 PF | $W_2=EI\ Cos\ (90°+30°)$ | +50% |

| | EFFECT ON $W_1$ OF CURRENT TRANSFORMER PHASE ANGLE ERROR | | EFFECT ON $W_2$ OF CURRENT TRANSFORMER PHASE ANGLE ERROR | |
|---|---|---|---|---|
| Phase Angle | 3-Phase Power Factor | | 3-Phase Power Factor | |
| Error | 100%—86.6% | 86.6%—0 | 100%—50% | 50%—0 |
| Leading Angle | Decreases | Increases | Increases | Decreases Neg. Comp. |
| Lagging Angle | Increases | Decreases | Decreases | Increases Neg. Comp. |

**VECTOR RELATION** of current and voltage in each wattmeter used in the two wattmeter method of measuring 3-phase power. Individual power factors and summary of effects on wattmeters are shown in the tables. **(FIGURE 1)**

## Ratio and phase angle errors

The ratio error is expressed as RCF (Ratio Correction Factor) and is equal to the percent error of the transformer which is

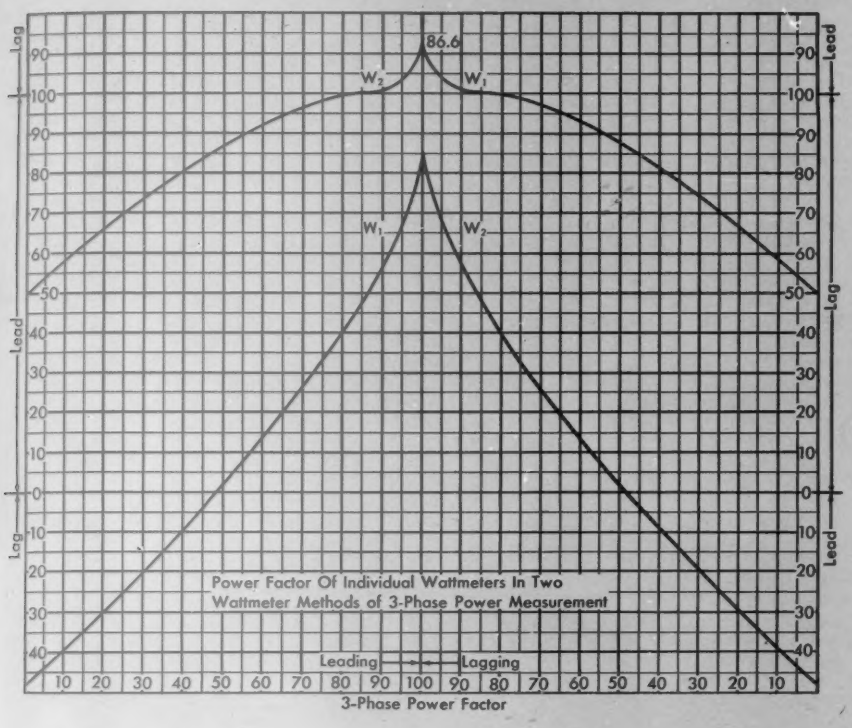
$$\frac{\text{true ratio}}{\text{marked ratio}} \times 100 - 100$$

This error is independent of the power factor of the primary circuit.

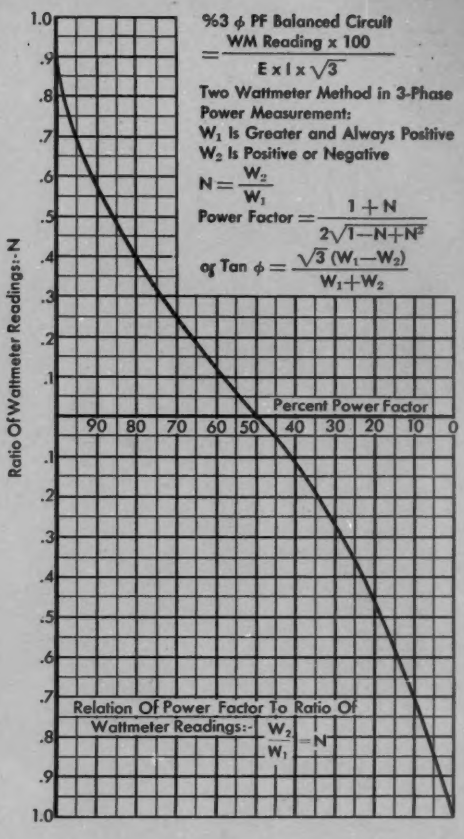
The phase angle error is one of varying significance, and the magnitude depends upon the power factor of the primary circuit being metered. The effect of the phase angle error upon the measurement of power increases as the power factor of the primary circuit decreases.

Various methods have been devised for evaluating the effect of the deviation in phase angle. One occurs in tabular form and is published in the chapter on "Instrument Transformers" in the "Handbook for Electrical Metermen." Explanations and instructions accompanying these correction methods are adapted to single-phase circuits. However certain precautions are necessary when three-phase circuits are involved.

**CURRENT AND VOLTAGE** both are measured with these oil-filled, 3-phase, 3-wire metering sets rated 27,600-115-volts and 10/20-5 amperes. Note double terminals for current measurement in bushings at the left.




**POWER FACTORS** under which wattmeter 1 and wattmeter 2 operate for all values of 3-phase power factors are illustrated above. **(FIGURE 2)**


%3 φ PF Balanced Circuit
= WM Reading x 100 / E x I x √3
Two Wattmeter Method in 3-Phase
Power Measurement:
W1 Is Greater and Always Positive
W2 Is Positive or Negative
N = W2/W1
Power Factor = (1+N) / 2√(1−N+N²)
or Tan φ = √3 (W1−W2) / W1+W2
Ratio Of Wattmeter Readings:- N
1.0 .9 .8 .7 .6 .5 .4 .3 .2 .1
Percent Power Factor
90 80 70 60 50 40 30 20 10 0
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
Relation Of Power Factor To Ratio Of
Wattmeter Readings:- W2/W1 = N

**RATIO OF WATTMETER** 2 to wattmeter 1 in the two wattmeter method of 3-phase power measurement for 3-phase power factors is shown. **(FIG. 3)**

## Three-phase factors differ

A three-phase power circuit may be metered by what is commonly termed the two-wattmeter method, or a polyphase two-element wattmeter may be utilized. In either case the corrections applied, due to the instrument transformer errors, give the same results and are handled in the same manner.

Phase angle corrections of three-phase power measurements are complicated by the fact that the power factor of a three-phase balanced circuit is different from the power factor of the circuit which actuates each of the single-phase meters or meter elements. In addition, the power factor on each of the meters differs one from the other. For this reason, each meter has a separate and different correction factor due to phase angle errors of the instrument transformers while the ratio error corrections are the same on each meter, assuming that the instrument transformers have like characteristics.

## Curves show current voltage relationship

Figure 1 shows the relation of current and voltage in the two-watt meter method of three-phase metering.

With unity power factor and a balanced three-phase circuit, XO and YO represent the current vectors, while XZ and YZ are the corresponding voltages.

Current XO flows through the current element of wattmeter $W_1$, while voltage XZ excites the potential coil. The current leads the voltage by 30 degrees.

Current YO flows through the current element of wattmeter $W_2$, while voltage YZ excites the potential coil. The current lags the voltage by 30 degrees.

For three-phase power factor of 100 per cent, $\phi = 0$ degrees

$W_1 = EI \cos 30°$ power factor of 86.6 per cent lead

$W_2 = EI \cos 30°$ power factor of 86.6 per cent lag

$$W_1 + W_2 = 2\,EI \cos 30° = \frac{2\,EI\,\sqrt{3}}{2}$$

$$\text{or 3-Phase Power} = EI\sqrt{3}$$

In a balanced circuit, $W_1$ is equal to $W_2$.

Figure 2 gives the individual power factors for $W_1$ and $W_2$ for the corresponding three-phase power factor.

A current transformer with a leading phase angle will cause a decrease in the $W_1$ reading, while a lagging phase angle will increase the registration. Conversely, a leading phase angle in a current transformer will increase the $W_2$ result, while a lagging angle will decrease it.

It can be seen from Figure 1 that as the three-phase power factor becomes lagging and decreases from unity, the current vectors revolve around the points X and Y. As the vector XO revolves through 90 degrees, the projection on XZ extended is always positive and in each case is always greater than the corresponding projections of YO on YZ extended. The projections of YO on YZ may be positive or negative.

The change from positive to negative registration is made when the three-phase power factor is 50 per cent.

$W_1 = EI \cos (60° - 30°)$ power factor of 86.6 per cent lag

$W_2 = EI \cos (60° + 30°)$ power factor 0 (See Figure 2).

$W_1$ thus shows positive registration, while $W_2$ is zero.

Below 50 per cent three-phase power factor the registration on $W_2$ is negative and the difference between $W_1$ and $W_2$ is recorded.

The relation between the two wattmeter readings and the three-phase power factor may be determined from Figure 3 where $N = \frac{W_2}{W_1}$

## Using the curves

To apply current transformer phase angle correction to three phase power registration, first determine the three phase power factor from the curve in Figure 3. Note that the wattmeter readings themselves will not indicate whether the power factor is lagging or leading. This must have been previously determined by an analysis of the load or by watching the meter indication when power factor correction is placed across the line.

Using this three-phase power factor we can obtain the power factor of $W_1$ and $W_2$ from the curves in Figure 2. Note that with a three-phase power factor less than 50 per cent lagging or greater than 86.6 per cent lagging one of the wattmeters is working with a leading individual power factor.

From the tables in Figure 1 determine whether the error is going to increase or decrease the registration, and proceed as in single phase corrections using Figure 4. For potential transformer phase angle errors, the corrections are diametrically opposite to those for current transformers. In other words where a current transformer phase angle error increases the wattmeter reading, a similar potential transformer phase angle error decreases the reading.

For practical purposes, the phase angle error for a given wattmeter can be found by numerically adding the current and potential phase angle errors.

## Solving a sample problem

Let us assume we have a two wattmeter metering hookup. It is desired to correct the readings and find the total power. The load is largely made up of induction motors. $W_1$ reads 64.0 Kw, $W_2$ reads 16.3 Kw.

C. T.$_1$
- Ratio error = 99.9
- Phase angle error = 5 minutes, leading

P. T.$_1$
- Ratio error = 100.5
- Phase angle error = 10 minutes lagging

C. T.$_2$
- Ratio error = 99.6
- Phase angle error = 15 minutes lagging

P. T.$_2$
- Ratio error = 100.4
- Phase angle error = 8 minutes leading

Combining C. T.$_1$ and P. T.$_1$
- Ratio error = $-.1 + .5 = .4$ or 100.4
- Phase angle error = +5 +10 minutes
  = 15 minutes (Positive)

Combining C. T.$_2$ and P. T.$_2$
- Ratio error = $-.4 + .4 = 0$ or 100.0
- Phase angle error = 15 lagging +8 leading
  = 23 minutes (Negative)

From Figure 3

$N = \frac{W_2}{W_1} = \frac{16.3}{64.} = .255$

or P. F. = 70% lagging

Referring to Figure 2
- P. F. of $W_1$ = 97% lagging
- P. F. of $W_2$ = 26% lagging

From Tables in Figure 1

(3-phase P. F. is 70%)
- Combined C. T. and P. T. leading phase angle (+15 minutes) error increases $W_1$ reading
- Combined C. T. and P. T. Lagging phase angle (−23 minutes) error decreases $W_2$ reading

Refer to Figure 4
- Lay straightedge across 100.4 on left column to +15 minutes (below center line) and read in 97% P. F. column (not shown — must be interpolated)
  $W_1$ reads 0.3% fast

And for $W_2$
- Lay straightedge across 100 in left column to −23 minutes (above center line) and read in 26% P. F. column (interpolate)
  $W_2$ reads 2.5% slow

True readings

$W_1 = (64.0)\ (100 - 0.3) = 63.8$ Kw

$W_2 = (16.3)\ (16.3)\ (100 + 2.5) = 16.7$ Kw

Or total power

$W_1 + W_2 = 80.5$ Kw

In the case of a leading three-phase power factor all the results are reversed 180 degrees.

## Handling 2-element wattmeter corrections

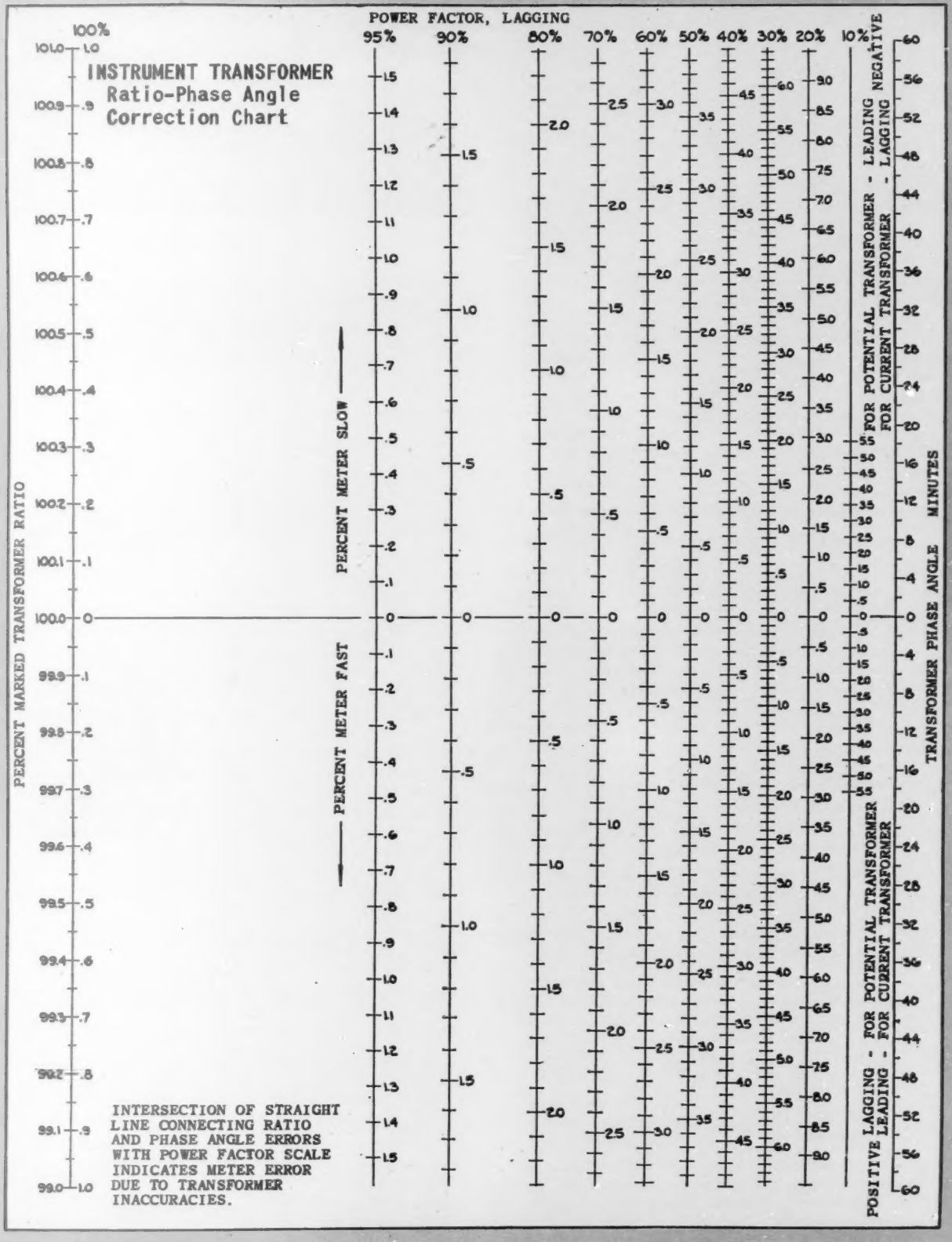
With the two-element wattmeter the separate wattmeter readings, $W_1$ and $W_2$ are not available. It is then necessary to have the current and voltage readings as well as the total power.

Assuming a three-phase balanced circuit the per cent three-phase power factor is $\frac{\text{Wattmeter reading} \times 100}{E \times I \times \sqrt{3}}$

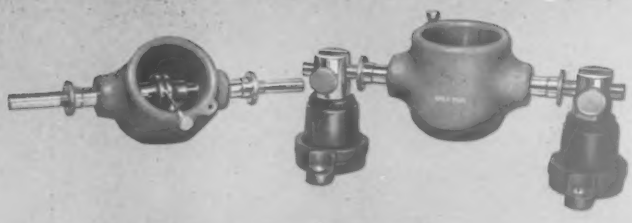
From Figure 3, the ratio of $\frac{W_2}{W_1}$ is determined.

$\frac{W_2}{W_1} = N$ and $W_1 \pm W_2 =$ Wattmeter reading.

Solve for $W_1$ and $W_2$ which values may be taken as the individual wattmeter readings. Then proceed as outlined above.


INSTRUMENT TRANSFORMER
Ratio-Phase Angle
Correction Chart
POWER FACTOR, LAGGING
95% 90% 80% 70% 60% 50% 40% 30% 20% 10%
100%
PERCENT MARKED TRANSFORMER RATIO
PERCENT METER SLOW
PERCENT METER FAST
TRANSFORMER PHASE ANGLE MINUTES
FOR POTENTIAL TRANSFORMER - LEADING NEGATIVE
FOR CURRENT TRANSFORMER - LAGGING
POSITIVE LAGGING - FOR POTENTIAL TRANSFORMER
LEADING - FOR CURRENT TRANSFORMER
INTERSECTION OF STRAIGHT LINE CONNECTING RATIO AND PHASE ANGLE ERRORS WITH POWER FACTOR SCALE INDICATES METER ERROR DUE TO TRANSFORMER INACCURACIES.

**NOMOGRAPH SHOWS** resultant error of phase angle and ratio errors for various power factors. Note difference between potential and current transformer corrections. Instructions for chart are in text. **(FIGURE 4)**



GAP FOR TESTING dielectric strength of oil. Portable transformer unit at left supplies variable voltage to test gap.

INTERFACIAL tension test.

# Tests for

**Not one but several tests are needed to determine oil condition.**


W. C. SEALEY
Engineer-in-Charge of Design
Transformer Section
Allis-Chalmers Mfg. Co.

NEW TRANSFORMERS are placed in service filled with dry oil especially refined for transformer operation. The chemical and physical properties of the oil change gradually during use, rendering it less suitable for transformer use. Each of its various compounds possess individual aging characteristics. In addition, the kind and rate of aging is affected by temperature, moisture and other materials with which the oil is in contact. Then, too, these materials may react with the oil or act as catalysts to accelerate the rate of aging. All these complicate the task of determining whether or not oil is suitable for continued transformer use.

Two types of tests are used to determine whether oil is suitable for further transformer service:

1. Direct or primary tests indicate the extent to which oil retains properties of new oil. These principal tests reveal whether oil has the dielectric strength, acid number, sludge, and steam emulsion number essential for effective transformer operation.
2. Overall or secondary tests measure properties of the oil which are not in themselves important for transformer operation, but which indicate comparatively any changes in the properties of the oil which may reflect undesirable characteristics. Their advantage lies in the lack of selectivity, since they provide an overall indication that there has been some change in the oil. The most important of these check power factor, interfacial tension, resistivity, and color.

No two tests give the same information. They vary in relative ease with which they can be made and the equipment and skill required. The time element also varies from one extreme to the other.

Each test contributes information concerning the suitability of the oil for service in transformers. Results from the various tests indicate more conclusively whether oil is safe for continued use or whether it should be reclaimed or replaced. Each of the tests commonly used is described and discussed individually.

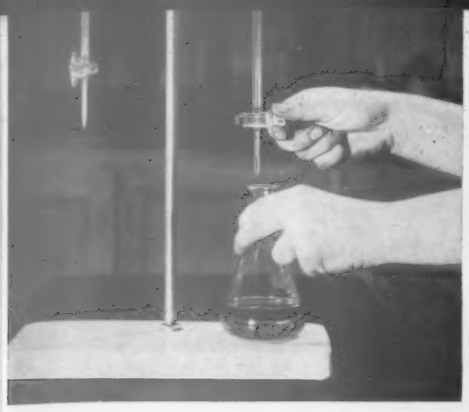
Samples of test oil should be carefully obtained and placed in thoroughly clean and dry containers, preferably large mouth glass bottles with a cork or glass stopper. Every precaution should be taken in drawing and storing oil to protect it against contamination. Sample oil should be taken from sampling valve at the bottom of the transformer tank, with sufficient oil drawn off first to assure that the sample will contain oil from the tank and not oil stored in the sampling pipe. Further details of the methods of sampling oil may be found in ASTM D923.

## Primary testing of used oil

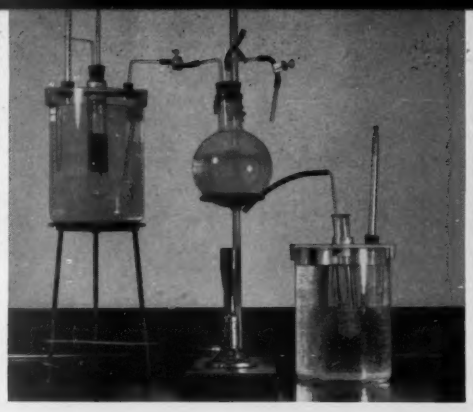
Direct or primary tests indicate the extent to which the oil retains the desirable properties of new oil. The most common of these tests are used for determining the dielectric strength, acid number, sludge, and steam emulsion number.

*Dielectric Strength:* Tests for a direct quantitative measure of dielectric strength, a necessary property of transformer oil since oil is used as an insulating material in transformers, are the most common made on transformer oil.

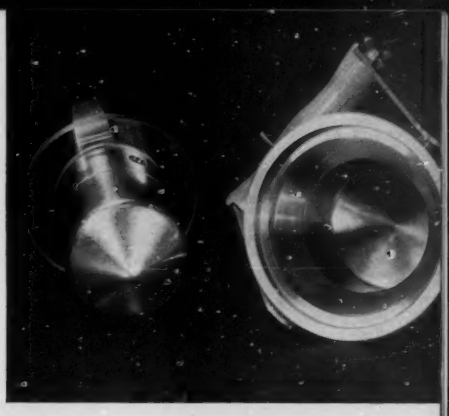
The oil sample is placed in a clean standard test cup rinsed out with a portion of the oil to be tested. The cup contains two disc terminals, one inch in diameter, spaced exactly one-tenth inch apart. Sixty cycle voltage is applied across the gap of the oil filled cup and gradually increased until break-



NEUTRALIZATION test.



STEAM EMULSION test.



METAL CELL for testing power factor.

# r Transformer Oils

down occurs. An average breakdown voltage of several tests is necessary to secure consistent results. Detailed instructions for making the test are given in ASTM D877.

Breakdown voltage for transformers in service should be at least 22,000 volts. New oil should have a dielectric strength of at least 26,000 volts, but by filtering to eliminate moisture a dielectric strength of over 30,000 volts can be obtained.

Generally water, dirt or other contaminants may reduce the dielectric strength of the oil. If the dielectric strength has been lowered by water contamination, it can be conditioned by drying the oil in a filter press. Drying can also be accomplished by a centrifuge or by vacuum treatment of the oil.

The dielectric strength test is simple to make and does not require a high degree of skill, although care is necessary in making it.

*Acid Number:* Transformer oils tend to become acid in service. The acidity test is used as an indication of changes in the oil condition and aging under service conditions. Some of the acid compounds produced by aging may attack insulating material and the metal parts of the transformer. Consequently, a low acid number is desirable.

The acid number of an oil is the number of milligrams of potassium hydroxide required to neutralize the acid in one gram of oil under specified test conditions. Usually, it is made by heating a sample of the oil in contact with an alcohol-water solution to the boiling point and neutralizing the mixture, while hot, with a potassium hydroxide solution using the color change of phenolphthalein to determine the point of neutralization (color indicator titration, ASTM D663).

The acid number can also be determined by electrometric titration. The oil sample is dissolved in a specified titration solvent and the mixture is neutralized with a standard potassium hydroxide alcoholic solution. Neutralization is indicated by the electrical potential between two electrodes immersed in a glass cell. By plotting the voltage measured across the electrodes versus the quantity of neutralizing solution added, the neutralization point may be determined as the point on the curve where the potential changes most rapidly with a small change in the quantity of neutralizing material added (ASTM D664).

For new oil, the acid number should not exceed .03. While high acid numbers of the order of .5 to 1 with no evidence of sludge formation may not be serious, values as high as these indicate that the oil should be examined for other evidences of deterioration. High acid content is not always injurious, since acidic compounds produced do not always attack the insulating material and metal parts of the transformers. Transformer oil with a high acid number and considerable sludge formation should be replaced. These tests are most readily made in a chemical laboratory and require considerable care and skill. Precision in determining acidity is difficult to obtain by the use of a color indicator on used oils which darken with use.

*Sludge Determination:* As transformer oil ages, it forms solid material or sludge. Sludge deposits on transformer core and coils reduce the rate of heat dissipation to the oil and clog oil ducts, reducing oil circulation and the rate of cooling. Sludge may also act as a catalyst to increase the rate of aging of the oil.

Tests for sludge consist of separating sludge by filtering and either estimating the quantity on a comparative basis or weighing it. A method of determining the amount of sludge in oil is contained in ASTM D670. Tests for sludge in oil are most easily made on a comparative basis owing to the difficulty in making quantitative measurements for the small amount usually found.

When oil contains any considerable amount of sludge, it should be filtered to remove the sludge and watched for further sludge formation. If it continues or if there is any considerable amount of sludge accompanied by high acidity, it is best to replace the oil. Considerable skill and experience is required for making either comparative or quantitative measurements of sludge since as many different results are obtained on the same oil as there are individuals testing it.

*Steam Emulsion Number:* A low steam emulsion number is a desirable characteristic of transformer oil since such oil tends to permit water which enters the transformer to separate and precipitate to the bottom of the tank. If the water remains in suspension, it may act as a catalyst to hasten oil deterioration and may also lower the dielectric strength.

The steam emulsion number is determined by blowing hot steam through a sample of cold oil until the liquid volume in the tube has doubled. Steam is then disconnected and the test tube placed in a hot bath. The time in seconds

required for a specified quantity of the oil to clear is the steam emulsion number (ASTM D157).

The steam emulsion number for new oil should not exceed 25 seconds. For used oils, it may be several times this figure. This test requires considerable experience to perform and to obtain reproducible results. The value of a steam emulsion test and its correlation with service experience with transformer oils is still a controversial subject.

## Overall tests measure physical properties

Overall tests for transformer oil measure its physical properties which change as oil ages. In themselves, they are not essential for satisfactory transformer operation.

For example, the color of an oil is of minor importance for transformer use, although a light colored oil is the easiest to inspect for sludge or color change to show the effect of aging. However, if a jet black oil was superior in its major characteristics to all other oils, such an oil could be used. It is possible by extensive refining to obtain a water clear transformer oil on which color changes can be most easily observed. Because such oils are less stable than slightly darker oils, they are seldom used.

A similar situation exists with reference to power factor. Transformer oils of extremely low power factor can be manufactured, but since power factor is of minor importance in operation, no sacrifice of the major properties required by good transformer oil can be justified to obtain an extremely low power factor. A good new oil may have either a high or low power factor. Interfacial tension and resistivity are also of minor importance in themselves, but they generally change as oil ages.

Overall tests are useful for furnishing an indication as to whether direct tests should be made to determine whether or not aging has affected the serviceability of oil. The most important of these test oil for power factor, interfacial tension, resistivity, and color. Since the overall tests are affected by a variety of changes which occur in the oil, close correlation between them cannot be expected and is not obtained.

*Power Factor:* The quantitative value of power factor of an oil is of minor significance. An increase in the power factor of oil during service indicates some change taking place, usually caused by moisture, the addition of foreign substances or changes taking place in the oil.

The power factor is determined by placing a sample of the oil in a suitable insulated test cell, applying an a-c voltage (usually 60 cycle) to the electrodes of the cell and measuring the power factor of the power supplied to the test cell. The voltage gradient applied should be considerably below the corona level.

Test cells used for power factor measurements consist of metal parts insulated from each other in an oil container. The two metal parts may be enclosed in glass or the oil container itself may comprise one of the metal electrodes.

A common form of circuit used to measure power factor is a Schering bridge. Power factor can also be calculated by measuring the current, voltage and watts loss in the cell. Details of methods of making power factor tests are described in ASTM-D924.

On new oil, the power factor may be as low as .02 percent in some cases. Good oil in service may have a power factor of several percent. A rapid change of oil power factor in service indicates the desirability of making primary tests on the oil, particularly those for dielectric strength, acid number and sludge. A slow rate of change of oil power factor does not necessarily mean that the oil is in good condition for operation. It may mean that the changes taking place may not affect power factor.

*Interfacial tension:* The interfacial tension test is used to indicate changes in the condition of transformer oil and is particularly sensitive when these changes are in the initial stage. Since the value of interfacial tension measured can be affected by many of the properties of the oil, it gives an overall indication of changes which occur without being selective as to cause. The value of interfacial tension is affected by acidic compounds in the oil and also by peroxides, whether corrosive or not. These peroxides act as catalysts to accelerate oil aging and also promote corrosion of the materials of the transformer. Because of its response to substances which are undesirable in transformer oil, the interfacial tension test shows promise of becoming of direct significance in indicating desirable oil properties in addition to its value as an overall test.

The interfacial tension test is made by placing a sample of the oil in the upper half of a vessel partly filled with water and measuring the interfacial tension at the boundary surface between the water and the oil with a tensionmeter. A measurement is made of the force required to draw a platinum wire ring vertically upward through the horizontal surface which separates the oil from the water.

New oil may have an interfacial tension as high as 50 dynes per centimeter while oil which has been severely aged may have a value below 15 dynes per centimeter.

*Resistivity:* Changes in insulation resistance may be due to various causes. So far as operation is concerned, the resistivity of transformer oils is so high that it is of minor importance.

Resistivity of oil may be obtained on a sample of the oil in a test cell by measuring its d-c resistance. The test may be made by using one of the test cells described for power factor determination. The resistance may be measured by any of the common electrical means used for measuring high resistances, such as a megger or megohm bridge (ASTM D257).

Principal advantage of this test is that it can be conducted by relatively inexperienced personnel. It is not as responsive to as wide a variety of causes as the tests for power factor and interfacial tension. It is more selective than the other overall tests.

*Color:* The color of transformer oil is of secondary importance in determining the serviceability of oil for further use. The only advantage of lighter oils is that they facilitate the detection of contamination, sludge formation and determination of the acid number by color titration. Also, a change in color is some measure of aging on a comparative basis. The color of an insulating oil is determined by comparing the color of the transmitted light of the sample with that of color standards, the result being expressed numerically. The transmitted light through the sample is matched by eye to that of the glass color standard it approximates and is reported as the number of the ASTM color (ASTM D155).

Generally, new oil has a color of less than one. Used oils run as high as six. A rapid rate of darkening of the oil would indicate that tests for primary properties should be made to determine other evidence of deterioration.

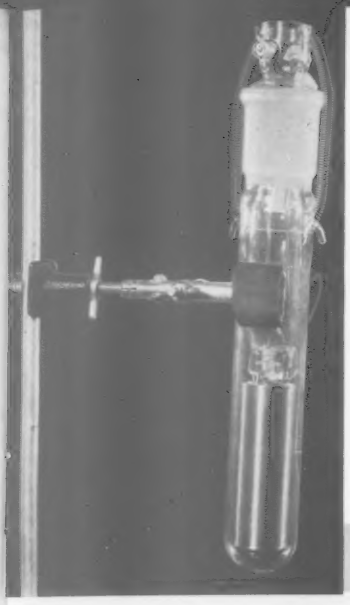
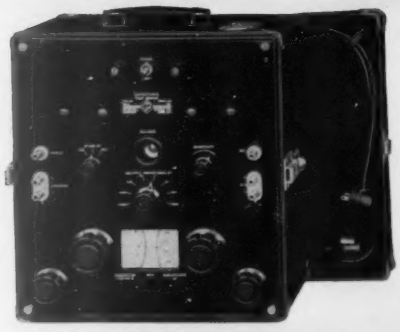


*Photo courtesy General Radio Co., Cambridge, Mass.*



CAPACITANCE BRIDGE for measuring power factor.

GLASS CELL for testing power factor.

COLOR testing of transformer oil.

This comparative test is easily made by experienced personnel. It is too selective and its correlation with desirable properties of the oil is not sufficiently close for this test to have great importance as an overall test. It is used chiefly because of its simplicity and ease with which it may be made and because it furnishes additional comparative data for estimating the condition of transformer oil.

*Aging Tests:* A prediction of the future rate of deterioration of oil already in service can be made by taking a sample of the used oil and subjecting it to aging in any one of the variety of ways used for sludge tests. Typical tests consist of heating a sample of the oil in an open vessel at 100 degrees C with exposure to the air either with or without the addition of catalysts such as copper, steel, or cellulose material. As the test proceeds, tests may be made on samples of the aged oil to determine any or all of the properties listed for the direct primary tests or the overall secondary tests.

Changes which take place during the aging test give an indication of the changes which may be expected to take place in the oil if it is continued in service. They may be interpreted on a comparative basis using as a reference the correlation obtained between similar tests and service experience in previous instances where the oil was continued in service. Such tests require experienced personnel and care in interpreting results.

## Conclusion

Because of the complex nature of oil and the ways in which it can change in service, probably no single test will ever replace all others for determining oil condition. Some tests are valuable as overall tests because their lack of selectivity gives an overall indication that there has been some change in the oil. Other tests are valuable because of their selectivity and their indication that there has been change in one of the desirable properties of the oil.

In determining whether an oil is suitable for service in a transformer, as complete data as possible is desirable, particularly the results of the primary tests which indicate the condition of the oil with reference to its desirable properties for service. While absolute values of properties are desirable, more information can be obtained from a record of the way these properties have been changing with time. Rapid changes in any of the properties are particularly significant in indicating oil deterioration. If the most significant of the tests indicate rapid deterioration, the oil should be replaced.

**SUMMARY OF TEST INFORMATION**

| Test | ASTM No. Describing Test | Typical Test Values | | |
|---|---|---|---|---|
| | | New Oil | Aged or Contaminated Oil | Units |
| **General** | | | | |
| Test Methods | D 117 | | | |
| Sampling | D 923 | | | |
| **Primary Tests** | | | | |
| Dielectric Strength | D 877 | 26,000 | 20,000 | Volts |
| Acid No. | D 663 — D 664 | .03 | 1.5 | |
| Sludge Determination | D 670 | None | .2 | % |
| Steam Emulsion No. | D 157 | 25 | 200 | Sec. |
| **Overall or Secondary Tests** | | | | |
| Power Factor | D 924 | 1 | 10 | % |
| Interfacial Tension | | 40 | 15 | Dynes per cm |
| Resistivity | D 257 | | | |
| Color ASTM — No. | D 155 | 1 | 6 | |

# Fundamentals of AC

PART IV OF VI PARTS*

DR. ERWIN SALZER
Consulting Engineer
Allis-Chalmers Mfg. Co.
Boston, Mass.

**Air break circuit breakers embody many of the basic principles of circuit interruption.**

INTERRUPTING a circuit, as explained previously, essentially consists in rendering the current path vulnerable by establishing an arc at a predetermined point of the circuit, and thereafter severing the path of the current by extinguishing the arc. The characteristics of the circuit determine the nature of any arc that may be established as a part of the circuit. They determine the extent to which the arc gap will be ionized by current flow and the extent to which it will be subjected to electric breakdown stresses on any attempt made at a current zero to effect permanent interruption. However, the nature of an arc in an interrupting device depends also on the interrupting device itself: the configuration of its parts, the materials of which it is made, its mechanical action upon the arc, its way of deionizing the arc path. Let us now consider interrupting devices *per se:*

## Classes of circuit breakers

Circuit breakers are divided into two broad classes, oilless and oil circuit breakers. The oilless class comprises air break and air blast (compressed air) circuit breakers. In air break circuit breakers the arc is initiated and extinguished in substantially static air in which the arc moves. In air blast circuit breakers a blast of air having a velocity close to that of sound is used for converting the arc path into an insulator. In oil circuit breakers oil plays a major role in the interrupting process.

Different kinds of circuit breakers overlap as regards common structural features (contacts, insulators, operating mechanisms), operating characteristics and common applications. Yet they are sufficiently different in many respects to warrant separate treatment.

Air break circuit breakers, among which the magnetic type is the most important, dominate the low voltage field. They are also used extensively in the relatively low voltage and interrupting capacity range of the so-called "power circuit breaker" field ranging up to 15,000 volts and 500,000-kva interrupting capacity. Applications include protection of lighting and power circuits of buildings, such as industrial plants, steel mills, power station auxiliaries and low capacity feeders.

We shall now investigate the basic principles underlying the operation of air break circuit breakers and the basic elements of which they consist. Both these principles and elements are also applicable in more or less modified forms to circuit breakers other than air break circuit breakers.

*Adequate coverage of circuit breakers requires the addition of another installment to the original five. Subsequent installments will deal with air blast breakers and oil circuit breakers, respectively.

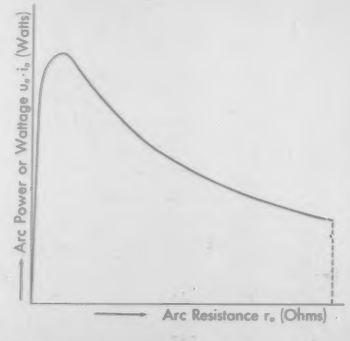
## Contacts pose design problem

The most vital parts of an interrupting device are the contacts. No wonder then that even the early design history of interrupting devices evidences certain refinements in the creation of contact arrangements.

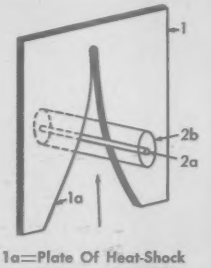
Progressive technical development confronts designers with the question of whether it is necessary or desirable to substitute a plurality of elements, each capable of performing but one single function in a highly effective or efficient way, for one single element capable of performing several functions, yet only in a less effective or relatively inefficient way. This question, ever-present in the design of interrupting devices, manifested itself very early with regard to contact arrangements.

Copper has a low specific resistance (about 1.72 microhms per cubic centimeter at 20 degrees centigrade) and a high specific heat (0.09 cal./gram/degree centigrade within the temperature range of 1 to 100 degrees centigrade). For these reasons contacts of copper are well suited for carrying current permanently without excessive heating. Yet copper has a low melting point (1083 degrees centigrade) and copper vapors are highly ionized at relatively low temperatures. Consequently, copper contacts have a tendency to "freeze" or weld, hence it is relatively difficult to extinguish an arc formed between a pair of copper contacts.

Tungsten has a high specific resistance (in the order of 6 microhms per cubic centimeter at 20 degrees centigrade) and a low specific heat (0.034 cal./gram/degree centigrade within the temperature range of 20 to 100 degrees centigrade). For these reasons tungsten is not well suited for carrying currents permanently. But tungsten has a high melting point (3380 degree centigrade) and tungsten contacts have little tendency to vaporize and form a highly couductive bridge of metal vapor across the contact gap. Hence it is relatively easy to extinguish arcs between tungsten contacts.




**CURVE SHOWING** watts dissipated in the resistance of a circuit when resistance is varied while circuit voltage is being maintained constant. **(FIGURE 1)**




1a=Plate Of Heat-Shock Resistant Material
1b=Inverted V-Shaped Slot
2a=Arc Core
2b=Envelope Of Arc

**BARRIERS HAVING** an inverted V-shaped slot for extinguishing arcs by constriction are a basic element of circuit breaker design. **(FIGURE 2)**

# Circuit Interruption

As a result, interrupting devices are frequently provided with a pair of copper contacts for carrying the current permanently, in addition to a pair of contacts of tungsten or a similar material that come into play only during the interrupting process. The contacts for carrying current permanently are referred to as main contacts and those between which the arc is drawn as arcing contacts.

Copper contacts have a tendency to form tough films of copper oxide on their surface. Since such films have a high resistance, their formation should be precluded on main copper contacts. This can be achieved by silver surfacing. Instead of tungsten, arcing contacts may be made of solid, powder metallurgical mixtures, produced by sintering, of tungsten and other metals. There are also various alloys suitable for making arcing contacts.

Sometimes a third pair of contacts, known as tertiary contacts, is added for one reason or another.

## Arc elongation

The arc which is initiated by initial separation of a pair of cooperating contacts is progressively elongated the farther the contacts are drawn apart. Elongation of an arc results in increased cooling and deionization by diffusion. This, in turn, causes progressive increase of the arc burning voltage and of the reignition voltage until a current zero is reached when the dielectric strength of the arc gap exceeds permanently the recovery voltage which the circuit impresses upon it.

Owing to the high temperature of the arc relative to the surrounding medium, the arc is subjected to strong convection currents. Where a pair of cooperating contacts is separated horizontally, resulting in the initiation of a horizontal arc, the heat of the arc and resultant chimney effect causes the arc to rise vertically and to form an upward loop, whereby its length may become considerably greater than the shortest distance between the separated contacts. When the elongation of the arc exceeds a certain limit, the resulting increase of the reignition voltage may render it impossible for the recovery voltage to reestablish the arc after its extinction at current zero.

As the arc rises and loops, the arc column leaves behind it a contaminated, i.e. relatively hot and ionized area, and is continually and continuously transferred into uncontaminated space, whereby the arc is continually and continuously cooled and diluted.

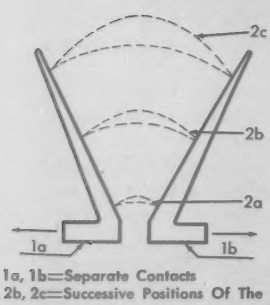
The combined effects of all these single factors, with particular emphasis on progressive increase of arc length, are comprised in the term "circuit interruption by arc elongation."

Arc elongation is the earliest method in design history used for interrupting a circuit. In any circuit breaker, whatever its underlying design principle may be, arc extinction is preceded by elongation of the arc from zero length to some predetermined length. Hence, there is no breaker, however modern and advanced its design may be, that does not rely on arc elongation to some extent.

In the low voltage, low and medium capacity range, arc elongation still plays an important part in the operation of interrupting devices, particularly in combination with other methods of arc extinction. However, so far as other applications are concerned, particularly the superhigh voltage field, arc elongation has been largely superseded by other more effective arc extinguishing methods.

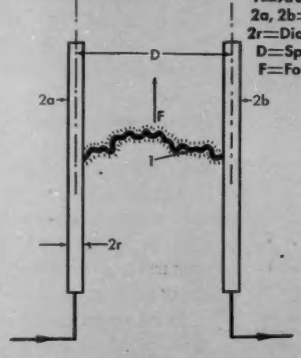
Arc elongation is a relatively ineffective interrupting means inasmuch as the rate of cooling and deionization increase slowly with increasing arc length. Hence, where a given arc is being cooled and deionized merely by elongation, without resorting to additional more effective means, a relatively large amount of elongation will be required for interrupting the circuit.

A large amount of arc elongation calls for relatively large, bulky, interrupting structures and, if the voltage is very high, the size, weight and cost of such structures tend to become prohibitive. Large amounts of arc elongation are also conducive to dissipation of large amounts of arc energy, i.e., generation of large amounts of heat, which may be difficult to control and tend to maintain the arc gap in an ionized state. These and other reasons limit the permissible amount of arc



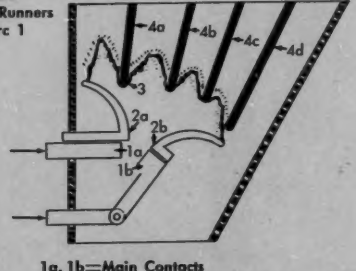

1a, 1b=Separate Contacts
2a, 2b, 2c=Successive Positions Of The Arc

**ARC HORNS** represent another extremely important basic element in the design of circuit breakers and switches. **(FIGURE 3)**




1=Arc
2a, 2b=Arc Runners
2r=Diameter Of Arc Runners
D=Spacing Between Arc Runners
F=Force Acting Upon Arc 1

**ARC RUNNERS,** operating on the same fundamental principles as arc horns, accelerate motion of the arc. **(FIGURE 4)**




1a, 1b=Main Contacts
2a, 2b=Horn-Shaped Arcing contacts
3=Arc
4a — 4d=Arc Restraining Metal Barrier

**ARC RESTRAINING** metal barriers subdivide long arcs into several serially related short arcs. **(FIGURE 5)**

elongation, making it necessary to supplement arc elongation by more effective interrupting methods.

There are, however, a number of reasons which may justify considerable amounts of arc elongation and outweigh the resulting disadvantages. The larger the amount of contact separation and consequent arc elongation, the easier it is to establish dielectric strength in the gap formed between the separated contacts and the less cooling and deionization per unit arc length is required. This makes it possible to resort to arc cooling and deionizing structures simple and inexpensive to manufacture, and these advantages may make up for their relative lack of compactness.

Another reason for tolerating arc elongation is increasing contact life. Where arc terminals are permitted to remain throughout the arcing time at the points of the contacts where the arc was initiated, contact erosion tends to be large. Moving the arc terminals along the contacts away from the points of arc inception to other points limits the amount of contact erosion. Generally, the amount of elongation of an arc incidental to such arc transfers is perfectly acceptable.

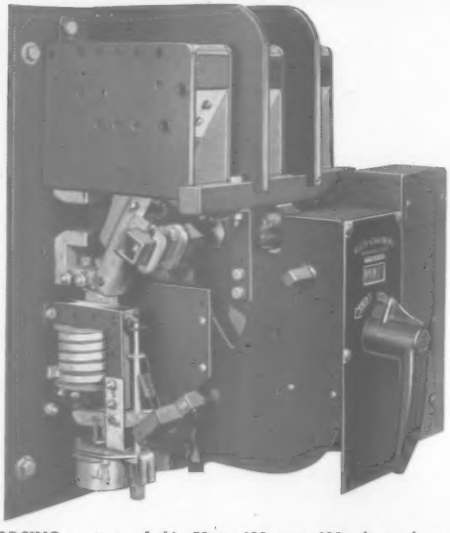
## Relation of arc elongation to energy

The amounts of power and energy dissipated in an arc in form of heat depend on arc elongation, as shown in Figure 1.

The illustration shows the basic power or wattage $I^2$-r versus resistance r relation applicable to any circuit including a variable resistance r. The above relation applies also to arc power or arc wattage which is equal to the product of the square of the arc current $i^2_a$ and the arc resistance $r_a$, or the product of arc voltage $u_a$ times arc current $i_a$. Hence Figure 1 illustrates the relation of arc wattage $u_a \cdot i_a$ versus arc resistance $r_a$.

Arc resistance, or the resistance of the arc space, is an immediate indication for the degree of ionization of the arc space and increases as the degree of ionization of the arc space decreases and the arc gap recovers its dielectric strength. Conversely, arc or arc space resistance decreases with increasing ionization of the arc gap. Because of this parallelism between arc or arc space resistance and ionization, deionization and dielectric strength, many problems can be considered and solved simply in terms of arc or arc space resistance and elementary circuit theory without resorting to the more complex concept of the ionized state.

As long as arc resistance is small, which is the case when as the arc is short, the arc wattage is relatively small. Arc



**MAIN ARCING** contacts of this 50 to 600-amp, 600-volt a-c low voltage air break circuit breaker are shown below the arc chute. The position of diverging arc-constricting barriers arranged inside of the arc chute is indicated by screws which can be seen on the chute's outer side.

wattage increases rapidly as arc resistance is increased until it reaches a peak value. Further increase of arc resistance results in a decrease of arc wattage. Obviously, any interruption of a circuit involves progressive increase of arc resistance from zero to a certain critical value sufficient to preclude reignition of the arc after a current zero.

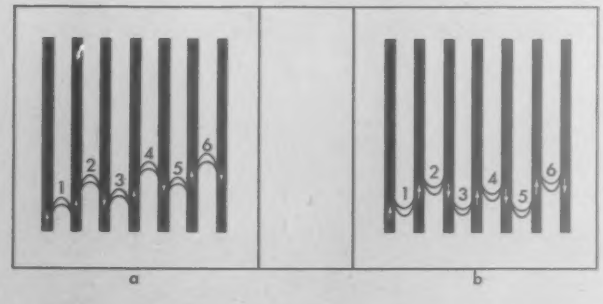
The arc energy, defined as $\int_0^T u_a \cdot i_a \cdot dt$, depends on the arc wattage vs. time characteristic and is equal to the area under that curve. Arc energy increases with increase of the time required for introducing sufficient arc resistance into the circuit to prevent arc reignition after some current zero. Since it takes considerable time to increase the arc resistance to that critical value if no other means than arc elongation are available for that purpose, additional means for rapidly increasing arc resistance to the critical point must be applied where limitation of arc energy is essential.

## Arc constriction

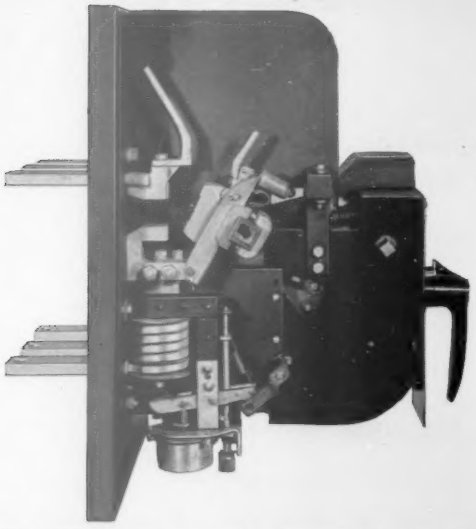
A much higher voltage is required to maintain an arc in a small hole or narrow slot than is needed to maintain an unconfined arc. The voltage gradiant required for maintaining an arc increases rapidly with the decrease of hole size or slot width, respectively.

The behavior of arcs confined in small holes or narrow slots differs significantly, depending upon the nature of the material by which the holes or slots are defined. Under similar circumstances the reignition voltage of an arc burning in a small hole or narrow slot in a material of mineral origin, e.g., soapstone, or a ceramic material, is generally smaller than the reignition voltage of an arc burning in a small hole or narrow slot in a material of organic nature, e.g. fiber or a synthetic resin.

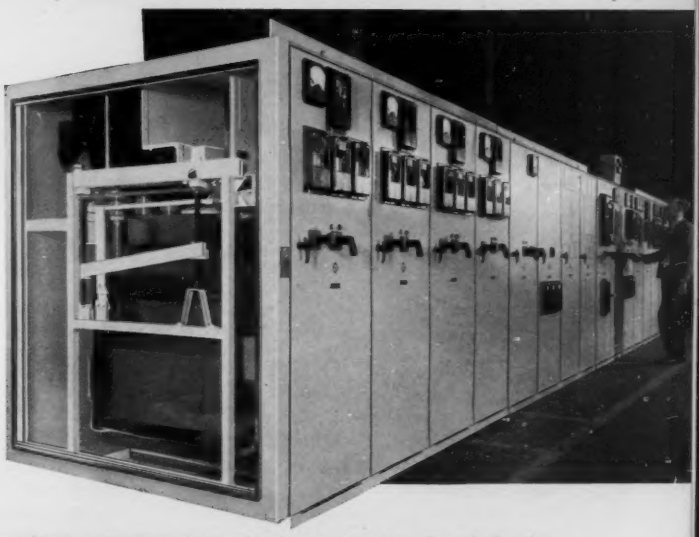
The effectiveness of organic substances for circuit interruption by arc constriction is due to the fact that such sub-




**DRAWING SHOWING** travel of arcs between stacks of parallel metallic interrupter plates at different speeds. Arcs at left (a) move at a relatively slow speed. Because of the increased strength of the magnetic field, arcs at right (b) travel at relatively high speed. **(FIGURES 6a and 6b)**



**ARCING CONTACTS** and arc horns of the same typical low voltage air break circuit breaker (arc chute removed) are shown above. Magnetic trip mechanism on these breakers can be set to give practically instantaneous tripping at fifteen times normal current.



**MAGNETIC AIR BREAK** circuit breakers, such as seen through the glass panel on this 5-kv, 100,000-kva switchgear, incorporate many of the design principles discussed in this installment. Unit was shipped to a midwest college. Glass plate will enable electrical students to study operation.

stances decompose under the heat of the arc, resulting in the evolution of relatively cold un-ionized gas, which diffuses into the arc stream. The gas so introduced into the arc stream increases the arc voltage, since it must be brought up to arc temperature and ionized. The arc is further cooled by the amount of heat necessary for decomposing the organic substance.

Gas escaping from a small hole or narrow slot where it evolves under the action of the arc may reach velocities in the order of several hundred yards per second, having an intense scavenging and deionizing action. Such a blast of gas escaping from an arc-filled small hole or narrow slot is, of course, highly turbulent, thus greatly increasing the deionizing action of the blast. The amount of material which is decomposed during arc extinction in a small hole or narrow slot need not be large, provided that the rate of decomposition is sufficiently high to effect final interruption of the circuit at an early current zero.

On the other hand, where the current under interruption is large, arc extinction by constriction in holes or slots in a gas evolving organic material becomes rather difficult, unless the arcing time is extremely short. Relatively large currents and long arcing times may result in prohibitive deterioration of organic materials under the heat of the arc. The gases evolved from such materials may be combustible, and disposing of such combustible gases may raise particular design problems.

The basic structure for extinguishing an arc by constriction is shown diagrammatically in Figure 2. Plate 1 is made either of a heat-shock resistant ceramic material, e.g., a zirconium compound, or an organic material as, for instance, fiber, and is provided with inverted V-shaped slot 1a. The slope at the lower portion of slot 1a is less than the slope at its upper portion. An arc 2 is initiated at the lowermost portion of slot 1a and rises because of thermal effect, or is otherwise transferred to the upper slot portion. As the arc reaches the portion of the slot 1a close to its upper end, the squeezing or pinching action of the edges of the slot 1a upon the arc becomes more intense, thus sharply limiting the cross-section of the arc and confining it to a progressively decreasing space.

While a great variety of structures have been devised for effecting circuit interruption by arc constriction, the above arrangement is a representative embodiment of their underlying design principle.

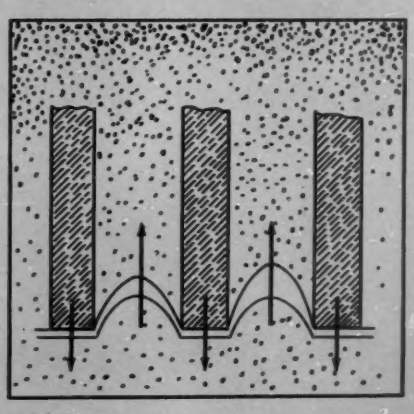
## Arc horns elongate arc

The design principle underlying arc horns is shown in Figure 3.

When the horn-shaped contacts 1a and 1b part, an arc is initiated close to the lowermost point of the device. Thereafter the arc rises by reason of heat generation and of the electromagnetic effect which occurs wherever the path of a current is loop-shaped, as in the present case. Successive positions of the arc are indicated in Figure 3 by 2a, 2b and 2c. This figure also indicates that the upward movement of the arc terminals, or arc roots, tends to be somewhat slower than that of the intermediate, upward looping portion of the arc, owing to a tendency of the arc terminals to stick to relatively

**ARC MOVED** against insulating plates cool at points where they engage barriers. **(FIGURE 7)**

Arrows Pointing Upward = Arc Propelling Forces Arrows Pointing Downward = Stream Of Gas Evolved From Arc Restraining Edges Of Plates



hot metal parts. In spite of this tendency, the arc terminals are pulled in an upward direction by the intermediate, upward looping portion of the arc.

Since the cathode spot of the arc is continually transferred from relatively warm to relatively cold portions of the arc horns, thermionic electron emission is inhibited. As the arc rises within the gap formed between the horns it is subjected to elongation. Its rapid movement through the surrounding cool medium accelerates deionization by cooling and diffusion of electrons and ions out of the arc zone and of electrically neutral gas into the arc zone. All these effects upon the arc combine to increase its burning and reignition voltage which may well exceed the breakdown voltage at the shortest gap length between contacts 1a and 1b.

Whenever this occurs, the arc may restrike at the point where the gap length is shortest, whereas the old arc, at the upper part of the horns, ceases to burn, the resistance of the path of the new arc being smaller than that of the old one. The new arc rises exactly the same way as its predecessor and thus the process of arc elongation, cooling and deionization is repeated. There may be a number of restrikes and subsequent elongations of the arc until interruption of the circuit is completed. The intervals elapsing between the times of formation of an arc where the gap length is shortest and the times when the arc reaches a relatively elevated level between the arc horns may be sufficiently long to permit a substantial recovery of the dielectric strength of the gap at its shortest length. Inasmuch as the arc is moved away in these intervals from the point of shortest gap length to another place, its effect on the dielectric recovery at the point of shortest gap length will be limited.

Most interrupting devices depend on motion of the arc relative to structural elements and relative to the surrounding medium. Arc horns are just one of many, though an extremely important, basic structure for achieving this end.

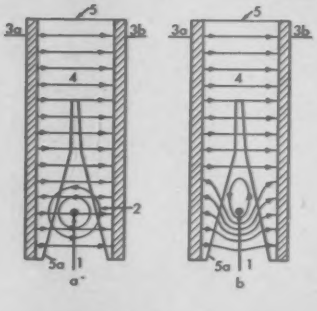
## Arc runners accelerate arc motion

Another basic structure for moving arc which is closely related to arc horns is known as arc runners, shown in Figure 4.

An arc 1 is established by some appropriate means, not shown, between the two spaced, parallel, vertical rods 2a, 2b, and moves up in the same manner as it does on arc horns. In case of rods of circular cross-section, the radius of which is r and the spacing between which is D, the total magnetic force acting upon the arc tending to move it upward may be expressed by the equation

$$F = i_a^2 \log \frac{D}{r}$$

where $i_a$ is the arc current.




Magnetic Blowout Field and Magnetic Field of Arc Current

1=Arc
2=Magnetic Field of Arc Current
3a, 3b=Poles of Electromagnet
4=Magnetic Blowout Field
5a=Barriers
5b=Inverted V-Shaped Slots

Magnetic Field Resulting from Magnetic Blowout and Arc Current Fields

**MAGNETIC BLOWOUT** is a means of transfering arcs in interrupting devices from one point to another. Its purpose varies. **(FIGURES 4a and 4b)**

## Arc restraining metal barriers

The switch or circuit breaker shown in Figure 5 comprises main contacts 1a, 1b and arcing contacts 2a, 2b with the latter provided with arc horns. Arc 3 drawn between arcing contacts 2a and 2b, is driven by thermal effect and by magnetic action against the edges of a stack of four spaced diverging metal plates 4a, 4b, 4c and 4d. If a hot cathode forms at each point where the arc is engaged by the plates, it tends to inhibit upward movement of the arc at the points of plate-engagement. Metal plates 4a to 4d thus subdivide a relatively long arc into several short arcs in series. The short arc sections situated between the arc-restraining edges of the plates loop into the interplate gaps, resulting in sufficient arc elongation to effect arc extinction.

## Interrupter plates break up arc

Figures 6a and 6b show a stack of parallel metal plates which could be substituted in an interrupting device, if desired, for the diverging plate arrangement shown in Figure 5. While it was assumed in Figure 5 that the arc is restrained at or close to the arc-engaging edges of the plates by the formation of hot cathodes, Figures 6a and 6b were drawn on the assumption that there is no such arc restraint. The original long arc is chopped by the stack of spaced plates into a family of serially related arclets, as in the case of Figure 5. However, in the case of Figures 6a and 6b the terminals of these arclets as well as the portion of the arclets situated between their terminals are caused to move at a high speed through the interplate gaps. This may be achieved by making the arc-splitting plates of smooth copper and by subjecting the arclets to an intense magnetic field, exerting considerable accelerating forces upon them. High speed motion of the terminals of the arclets along cool surfaces of copper plates inhibits the formation of hot cathodes with their abundant release of electrons which, in turn, makes it possible to effect high-speed motion of the arc terminals.

Cathodes formed on the copper plates turn into anodes after each current zero. The electrons situated immediately in front of these ex-cathodes or newly formed anodes are attracted to the newly formed anodes, where they are neutralized, resulting in extremely rapid removal of electrons from the regions immediately adjacent the ex-cathodes or newly formed anodes. Thus thin electron-deficient layers are formed in front of each electrode. Because of their electron-deficiency, these layers have a high dielectric strength, in the order of 250 crest volts. If each electron-deficient layer has a dielectric strength of p volts, and there are n plates in a given structure, arc reignition will not take place unless the recovery voltage impressed upon the gap exceeds $p \times n$ volts. Consequently, the interrupting ability of the device will increase with the number of plates utilized. Actually, the above computation is somewhat more complex because the total voltage is not equally distributed across a stack of spaced plates.

## Speed affects arcs

The operation of the structures of Figures 6a and 6b depends very much on the speed of travel of the arclets through the

interplate spaces. Where a group of short, serially related arclets is rapidly moved through the interplate spaces of a stack of parallel spaced metal plates, a reduction of pressure will occur on the "leeward" (away from the wind) surfaces of the arclets, and back pressure will be created at the opposite side. The difference in pressure on both sides of the arclets tends to establish a cross-flow of gas through the arclets opposite to the direction of their sweep through space. As a result of this cross-flow of air, a turbulent mixing will occur between the hot arc gases and the cold air through which the arclets are swept, greatly increasing the interrupting efficiency of the device.

High-speed motion pictures of the interruption process in an arrangement of the type shown in Figures 6a and 6b reveal that, with a given intensity of the magnetic arc propelling field, the arclets are substantially convex and travel at a certain average speed through the interplate spaces. As the intensity of the magnetic field is increased, the increased speed of travel of the arclets causes their shape to revert from convex to concave. This is apparently indicative of the magnitude of the cross-flow effect created by reason of the inertia of the ambient air combined with the high velocity of the arclets.

Figure 6a indicates, diagrammatically, a group of arclets moving in a magnetic field through the interplate spaces of a stack of spaced metal plates. Figure 6b shows the effect, in the same structure, of a great increase of the speed of arclet travel caused by an increase of the strength of the magnetic field.

Not all points of the original arc, split up by the plates into a multiplicity of arclets, reach the lower edges of the plates at the same time. Hence the race of the different arclets through the interplate spaces begins at different points of time. Those arclets (arclets 2, 4 and 6 in Figure 6a), which are most advanced at the beginning of the race, will be further accelerated by reason of electromagnetic forces resulting from the upward looping shape of the path of the current through the arclets and the adjacent plates. Conversely, the shape of the path of the current through other arclets (arclets 3 and 5 in Figure 6a) and through the adjacent barriers is a downward loop and the electromagnetic forces which are thereby set up tend to push these arclets back toward the lower edges of the barriers. Similarly, in the case shown in Figure 6b, some arclets will be subjected to accelerating, and some to decelerating, electromagnetic forces.

Circuit breakers of this type have been built in voltage ratings of 2.5, 5 and even of 15 kv. This type is ordinarily beyond the range of economic use when it comes to interrupting the relatively large currents and voltages encountered in power circuit breakers.

## Insulating barriers are widely used

In modern air break interrupting devices stacks of spaced insulating plates have largely superseded stacks of spaced metal plates (Figure 7). If an arc is moved against a stack of spaced insulating plates arranged edgewise with respect to the arc, the edges of the plates restrain further movement of the arc at the points of arc engagement, while the sections of the arc situated between the arc-restraining edges are more or less free to loop into the interplate gaps. The arc is cooled at the points where the arc engages the plates.

The heat of the arc may cause evolution of gas from the material of which the plates are made. This gas diffuses into the arc, resulting in cooling and reduction of the ion concentration of the arc stream. Arc elongation occurring in the interplate gaps increases the arc resistance. The column gradient depends largely upon the number of plates per unit of length and upon the width of the interplate gaps and increases rapidly as the former is increased and the latter decreased. The time required for a given amount of dielectric recovery of the arcing zone decreases as the number of plates per unit of length is increased and as the width of the interplate gaps decreased. There is, however, a limit to increase of dielectric recovery by increase of number of plates per unit of length and decrease of width of interplate gaps where small gap width precludes sufficiently effective venting of the arc gases from the arcing zone.

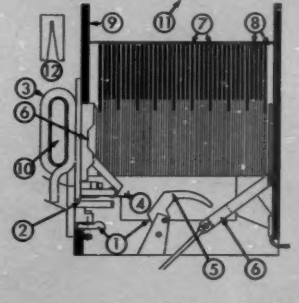
Both ceramic materials and materials of an organic nature may be used for making arc-restraining barriers for use in interrupting devices. If ceramic materials are used, heat-shock resistance and emissivity of electrons under the heat of the arc require particular consideration. Barriers of organic materials tend to release relatively large amounts of vapor and gases in nascent state, and the chemical nature of the latter is of importance relative to the suitability of any material for the purpose in hand.

Generally arc restraining insulating barriers are provided with inverted V-shaped arc-constricting notches of the kind shown in Figure 2 and thus also make use of the principle of arc constriction.

## Purpose of magnetic blowout varies

A magnetic blowout within the broadest meaning of that term is any means for setting up a magnetic field tending to displace the arc incident upon separation of a pair of cooperating contacts. The purpose of moving or displacing an arc may vary in different applications of the magnetic blowout principle, or a given application of that principle may have several different purposes. By subjecting an arc to the action of magnetic forces, the arc path may be caused to bulge and thereby become elongated. A magnetic blowout field may be used for transferring an arc from the point of initiation to a remote point of "liquidation," e.g., into narrow arc-constricting slots of insulating plates. A magnetic blowout may also be used for effecting high-speed turbulent motion of an arc through space, causing mixing of the hot arc gases with surrounding cool electrically neutral gas. Finally,

1=Main Contacts
2=Intermediate Stationary Contact
3=Magnetic Blowout Coil
4=Stationary Arcing Contact
5=Horn-Shaped Portion of Movable Contact
6=Arc Runners
7=Ceramic Barriers
8=Air Ducts
9=Arc Chute
10=Iron Core Blowout Magnet
11=Air Vent
12=Detail of Barrier Showing Inverted V-Shaped Slot



**CROSS SECTION** of a typical magnetic air break circuit breaker, rated five kv with a 150,000-kva interrupting capacity. **(FIGURE 9)**

magnetic fields may be used for protecting metallic arc-terminal-forming structures against excessive heating and consequent vaporization and erosion. To this end, the arc may be moved by a magnetic field along the arc-terminal-forming structure and, if desired, be kept in constant circular motion by magnetic field action.

Figures 8a and 8b are cross-sections through an interrupting structure or arc chute involving a magnetic blowout and comprising a number of parallel spaced vertical barriers 5 having inverted V-shaped slots 5a. Arc 1 is initiated at the bottom region of the arc chute. The magnetic field set up by the arc current is indicated by concentric circles 2. A substantially uniform magnetic field 4 is formed between the poles 3a and 3b of an electromagnet not shown in the figures. Superposition of magnetic fields 2 and 4 yields the resultant field shown in Figure 8b. The resultant field is strengthened toward the bottom and weakened toward the top of the arc chute. Since an arc, as in the case of any other electric conductor, moves, unless restrained, from the stronger to the weaker part of a magnetic field, the prevailing resultant field effects a movement of the arc in an upward direction at right angles to field 4 toward the narrow arc-constricting ends of the inverted V-shaped slots 5a.

## Flame suppressors cool and deionize

After complete cessation of current flow, a flame consisting of a body of hot ionized gas continues to persist for a certain period of time. The temperature and ionization of this body of gas are well below the temperature and ionization prevailing in the arc column. Accordingly, its breakdown voltage is relatively high. Nevertheless, there may be danger in permitting hot ionized gases to escape from an interrupting device, since there is a possibility that they might cause damage, or even result in an electric breakdown on the outside of the device, provided that there is a sufficiently high voltage gradient. Such a possibility can be avoided by providing the arc extinguisher or arc chute with some sort of flame suppressor, e.g., in form of a super-structure, for further cooling and deionizing the products of arcing after they leave the arcing zone and before they are released to atmosphere.

Flame suppressors are generally made up of stacks of spaced metallic cooling plates or barriers having a high specific heat such as copper plates. In order to distinguish between barriers which form a part of the interrupter proper and barriers which form a part of the flame suppressor, barriers of the former kind are often referred to as arc splitters, and the latter as flame splitters.

**CONTACT ARRANGEMENT** of circuit breaker in Figure 9, with interphase barriers removed, shows contacts of all three poles. **(FIGURE 10)**

## Typical air magnetic breakers

Figure 9 is a vertical section of a magnetic air break circuit breaker with a voltage rating of 5 kv and an interrupting capacity rating of 150,000 kva, while Figure 10 shows the contact arrangement of that breaker structure. The breaker is designed to blend judiciously most of the various design principles and elements which were singly analyzed before.

As long as the breaker is in closed position, the movable and stationary main contacts 1 are in engagement and the movable contact 1 also engages the intermediate stationary contact 2 and the horn-shaped stationary arcing contact 4. Interruption of the circuit is effected by moving movable contact 1 from left to right. First main contacts 1 part, then movable contact 1 parts from intermediate stationary contact 2 and, finally, movable contact 1 parts from stationary arcing contact 4. Separation of contacts 1 and 2 causes insertion of the magnetic blowout coil 3 into the circuit. Therefore, the magnetic blowout field is established before an arc is initiated by parting of contacts 1 and 4.

Arc initiation is like a violent explosion in that there is a release of large quantities of heat and generation of pressure at extremely rapid rates. The arc is driven in an upward direction by a combination of three forces: Thermal action, electromagnetic horn gap action caused by the upper horn-shaped portion 5 of movable contact 1 and the upper horn-shaped portion of stationary contact 4, and the action of the magnetic blowout field produced by coil 3. Consequently, the speed at which the arc is moved is high and so are the rate of arc elongation, increase of arc resistance and consequent reduction of arc current.

During the rapid rise of the arc its left terminal is pulled along the sloping horn-shaped portion of arcing contact 4 and the left vertical arc runner 6. Upon continued opening of movable contact 1, its horn-shaped portion 5 engages the sloping portion of an arc runner 6 situated at the right side of the breaker. The right arc terminal is rapidly transferred from horn-shaped portion 5 to the arc runner on the right side of the breaker and then pulled along that arc runner in a slanting and then vertical trajectory. Both arc terminals are finally halted as they reach the top ends of the vertical portions of their respective arc runners.

When initiated between the parting contacts, the arc is a high-current, large-diameter arc involving large amounts of energy. As it is driven upward by the magnetic blowout field, it is forced into V-shaped slots 12 provided in spaced ceramic barriers 7 arranged in parallel to form a stack. The height of slots 12 varies along the stack formed by barriers 7.

As the arc rises within slots 12, it is progressively converted into a low-current, small-diameter arc by elongation as well as by constriction and rapid travel through space, so that when it is finally halted at the top of the slots 12 and subjected to a final tortuous deformation on account of the different height of the slots 12, its ready extinction at an early current zero is assured.

When the actual interruption in such a modern circuit break is viewed through a transparent window in the arc chute, arc initiation and arc extinction appear to merge into one single flash. It is only by the use of ultra-high-speed motion pictures, projected in slow motion that a real appreciation of this amazing split-second achievement can be gained.

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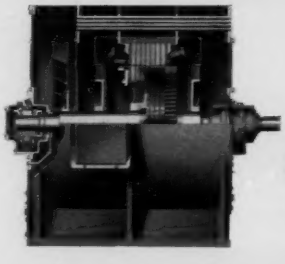

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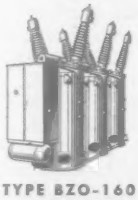

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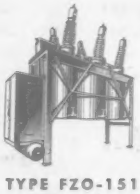
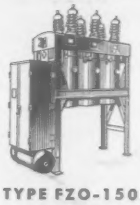


**TYPE FZO-151** . . . 69 kv . . . frame-mounted—5- or 8-cycle opening, 20-cycle reclosing.



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